Who has time to be green?
The 'double dividend' under bounded rationality and time constraints

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by

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Chapter 1

Introduction

We are facing an unprecedented man-made climate crisis. Our greenhouse gas (GHG) emissions are projected to heat up the planet by at least 1.5ºC compared to pre-industrial levels by 2040 (IPCC, 2022). The rise in temperature has already been documented and will further increase the frequency and magnitude of extreme weather events, such as droughts, floods, storms or wildfires. These in turn are expected to cause a wide range of natural, social and economic problems, including hunger, displacement, resource conflicts, biodiversity loss, and many more. To contain this crisis, as countries have pledged through the Paris Agreement, we need to lower our emissions through effective, efficient, and equitable mitigation policies.

Numerous policies have been suggested to curb GHG emissions. One of them is an environmental tax reform (ETR), denoting a revenue-neutral shift of tax incidence from desirable economic activity, such as labour, towards greenhouse gas (GHG) emissions. In other words, a shift from distortionary to Pigouvian taxes. Such tax reform is interesting for a number of reasons. First, economists widely agree on carbon pricing as the most efficient climate change mitigation policy, because it directs abatement of emissions to where it is least costly. Second, a carbon tax is relatively easy to implement, compared to the other main pricing instrument, a carbon market. Third, a carbon tax generates revenues, which can be used to achieve other policy goals or compensate inequitable effects.

Carbon taxation and the use of accruing revenues have been discussed extensively among researchers and policy makers alike. The idea that an ETR may lead to simultaneous environmental and economic benefits, especially when an environmental tax replaces a distortionary tax, has been termed the double dividend (DD).

A persistent terminological contribution of Goulder (1995) is the distinction between a weak and a strong DD. Both versions take environmental improvement through a tax shift as given. But while the weak DD assumes economic benefits of recycling the pollution tax revenues through cuts in distortionary taxes, as compared to returning them to households in a lump-sum fashion, the strong DD implies economic improvements compared to a situation with no tax reform. In its strong form, a double dividend thus means that environmental taxation can be based on pure efficiency grounds, regardless of its environmental benefits. This frees the policy-maker from estimating the exact magnitude of environmental damage, i.e. the social cost of carbon, which remains a fundamental uncertainty in climate policy design. The economic dividend can take different forms, including economic growth, higher purchasing power or additional employment. This thesis is focused mostly on the latter, for which the term employment double dividend (EDD) is common.

1.1 State of the art and research gap

The theoretical debate on environmental tax reforms and their double dividend potential has mainly taken place in environmental and public economics. Early proponents brought up the idea more than three decades ago (Pearce, 1991), and the many studies have given rise to several reviews and meta-analyses of the topic (Goulder, 1995; Bovenberg, 1999; Bosello et al., 2001; Freire-González, 2018).

Yet, there are a number of missing elements in the literature. First, models have traditionally used a representative, fully rational and atomistic agent, known also as *homo oeconomicus*. Some studies have devoted attention to agent diversity, such as by introducing skill differences (see e.g. Aubert and Chiroleu-Assouline, 2019; Metcalf, 1999; Fullerton and Monti, 2013). Differences between urban and rural populations within the same income group have been studied as well Douenne (2020). Nevertheless, multi-dimensional heterogeneity remains the exception rather than the rule. Other types of differences, such as the sector of employment, or gender are not analysed at all.

Besides a lack of heterogeneity among households, existing ETR models typically do not take insights from behavioural economics into account. Although evolutionary and behavioural economists as well as psychologists emphasise that most decision-making follows established rules or behaviours and happens under imperfect information, the fully-rational agent with complete information and perfect foresight is still the status quo in ETR analysis. I assume that economic agents are boundedly rational in the sense that they decide under imperfect information and rely on routines and habits.

The typical agent in an ETR model is also atomistic in the sense that it acts in a social vacuum. In reality, however, social context plays a important role in human decision making. Recently, Konc et al. (2021) have shown that socially-embedded preferences can have a great impact on the effectiveness of environmental policy, notably carbon taxation. As of yet, it remains unclear, whether the policy implications of existing ETR models hold up in a context of heterogeneous, social and boundedly rational human beings. These issues are particularly relevant today, because current discussions of carbon taxation go beyond efficiency and highlight certain social issues, such as fairness and acceptability (Klenert et al., 2018; Konc et al., 2022).

Another drawback of existing theoretical models is that they are often static. When they are dynamic, mostly taking the form of endogenous growth models, they typically are used to perform marginal analysis, relying on equilibrium and *ceteris paribus* assumptions and often focus more on growth than employment effects (see e.g. Bovenberg and De Mooij, 1997; Bovenberg and Smulders, 1995; Greiner, 2005; Nakada, 2010; Fernández et al., 2011). On the other hand, theoretical models with focus on employment effects have studied market distortions, but neglected the potential for evolutionary transformation processes that are likely to happen over the course of a successful low-carbon transition. To address such transformation, models need to account for innovation and structural change.

An additional shortcoming of existing theoretical models of the employment double dividend is that they lack explicit modelling of emissions or energy use. While some dynamic growth models take the externality explicitly into account, employment double dividend models simply distinguish between a dirty and a clean good, whereas polluting factors are commonly excluded from the production function. This leaves little room to study demand-driven innovation or even emission abatement, despite cost-efficient abatement of pollutants being one of the core ideas of the literature on Pigouvian taxation. This is closely linked to the previous drawback: without explicit modelling of fossil energy or emissions in a dynamic model, a transition away from these pollutants may not be fully understood.

Finally, models that focus on employment effects in particular would do good to distinguish between employment rates and work time. There are few studies that allow for discrete and intensive labour supply, i.e. whether an individual is employed or not as well as how many hours they work. If a policy maker aims for a reduction in unemployment, an increase in labour supply through longer working hours per person, instead of the creation of more jobs is undesirable. Yet, many models do not make this distinction.

In sum, there is a lack of systematic theoretical exploration of ETR in a dynamic environment with heterogeneous social agents and endogenous pollution processes. The aim of my thesis is to fill this research gap by developing a model that can incorporate these elements.

1.2 Research questions and methods

The overarching research question of this thesis is "*What are the innovation, employment and climate impacts of shifting taxes from labour to carbon under bounded rationality?*".

To address this question, I develop an agent-based model (ABM) encompassing the above-mentioned elements: boundedly rational and heterogeneous agents, who interact with each other, a trade-off between time for consumption and work, and energy use during production as well as consumption. Chapter 2 defines basic elements of the ABM by asking: *Which are relevant agent characteristics, behaviours and interactions that may affect the policy outcome in terms of an EDD and innovation?* Recognising the importance of the trade-off between work and consumption time for an EDD, Chapter 3 investigates this relationship empirically: *How does work time relate to leisure activity structures and related energy consumption?*

ABMs simulate complex system dynamics based on interaction of diverse agents. Farmer et al. (2015) have described ABMs as a particularly suitable modelling tool for studying climate policy, because of their ability to solve key issues in existing models, inter alia uncertainty, aggregation, heterogeneity, distributional implications and technological change. This means they differ considerably from the general equilibrium models (GEMs) typically used for ETR analysis. In order to make the results of this work more relatable to the existing literature, Chapter 4 builds a methodological link, moving from an existing GEM of ETR towards an ABM approach. *Can we replicate general equilibrium results using an agent-based model? How do we have to approach the modelling process differently when using ABM?* Finally, Chapter 5 extends the ABM of Chapter 4, including the factors we identified as most relevant in Chapter 2, to answer the main research question.

Regarding terminology, innovation refers to improvements in labour- or energy-efficiency during production and consumption. Employment effects are studied in a disaggregated manner for different household types and contain a distinction between employment rates and hours worked per individual. Climate impacts will be simplified to total energy use, assuming that all energy consumption causes greenhouse gas emissions.

The thesis puts a strong emphasis on discussing the new model assumptions and how the model relates to existing research. To arrive at the main model, I employ several other methods to support and validate my assumptions. These include literature review, econometric analysis and systematic comparison of models.

1.3 Thesis outline

The remainder of this thesis is structured as follows. Chapter 2 contains a synthetic literature review that explores the main mechanisms typically considered for an ETR and common modelling assumptions. Combining insights from various disciplines, missing elements, such as time use and bounded rationality, are derived.

Chapter 3 delves into the empirical side of one central element of the ABM: namely the nexus between work time, leisure activities and energy use. This involves combining time diary data and energy use data of various activities, followed by an econometric analysis of the relationship between time spent working and the energy-intensity of leisure. Performing the analysis for two different countries, Finland and France, using two distinct energy metrics, total energy and use energy, allows to observe cultural differences and the relevance of explicit energy modelling.

Chapter 4 examines whether an agent-based model can replicate the ETR results of a GEM. This involves exploring potential barriers to this methodological comparison. For this purpose an ABM is built based off an existing GEM and all propositions made by the original study are tested. These refer mostly to the possibility of a double dividend, combined with a (re)distributional goal. For this purpose, changes in purchasing power, consumption of a polluting good, and employment are assessed using a model with two household agent types and one representative firm. This model describes agents as atomistic, representative and rational, staying as close as possible to the original study.

Chapter 5 extends the agent-based model of Chapter 4 to study the main research question. It also builds on the two other preceding chapters, notable by including the new elements that motivate the ABM (Chapter 2), and using the empirical basis of one central new element, time use (Chapter 3). The model in Chapter 5 takes an activity-based *lifestyle* perspective, where households face a trade-off between consumption time, unpaid household/care work and paid labour.

Moreover, households are heterogeneous in terms of their (i) initial time endowment, (ii) levels of subsistence polluting consumption, and (iii) employment situation. The latter includes whether they are a member of the workforce or not, their sector of employment and their level of education. Their decisions are further characterised by habitual behaviour and imitation dynamics. In addition, I will test the consequences of variation in preferences, notably by examining strong preferences for leisure and for "green consumption". On the production side the model differentiates between three representative sectors, producing goods varying in labour- and energy-intensity during production, and in time- and energy-requirements during consumption. Firms are satisficers, innovating when triggered by falling profits or changes in demand.

Finally, Chapter 6 draws general conclusions about the studies reported in the various chapters. In addition, it provides ideas for further research.

References

Aubert, D. and Chiroleu-Assouline, M. (2019). Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82.

Bosello, F., Carraro, C., and Galeotti, M. (2001). The double dividend issue: modeling strategies and empirical findings. *Environment and Development Economics*, 6(1):9–45.

Bovenberg, A. (1999). Green tax reforms and the double dividend: an updated reader's guide. *International Tax and Public Finance*, 6(3):421–443.

Bovenberg, A. L. and De Mooij, R. A. (1997). Environmental tax reform and endogenous growth. *Journal of Public Economics*, 63(2):207–237.

Bovenberg, A. L. and Smulders, S. (1995). Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model. *Journal of public Economics*, 57(3):369–391.

Douenne, T. (2020). The vertical and horizontal distributive effects of energy taxes: A case study of a French policy. *The Energy Journal*, 41(3).

Farmer, J. D., Hepburn, C., Mealy, P., and Teytelboym, A. (2015). A third wave in the economics of climate change. *Environmental and Resource Economics*, 62(2):329–357.

Fernández, E., Pérez, R., and Ruiz, J. (2011). Optimal green tax reforms yielding double dividend. *Energy Policy*, 39(7):4253–4263.

Freire-González, J. (2018). Environmental taxation and the double dividend hypothesis in CGE modelling literature: A critical review. *Journal of Policy Modeling*, 40(1):194–223.

Fullerton, D. and Monti, H. (2013). Can pollution tax rebates protect low-wage earners? *Journal of Environmental Economics and Management*, 66(3):539–553.

Goulder, L. H. (1995). Environmental taxation and the double dividend: a reader's guide. *International Tax and Public Finance*, 2(2):157–183.

Greiner, A. (2005). Fiscal policy in an endogenous growth model with public capital and pollution. *The Japanese Economic Review*, 56(1):67–84.

IPCC (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., and Stern, N. (2018). Making carbon pricing work for citizens. *Nature Climate Change*, 8(8):669–677.

Konc, T., Drews, S., Savin, I., and van den Bergh, J. C. (2022). Co-dynamics of climate policy stringency and public support. *Global Environmental Change*, 74:102528.

Konc, T., Savin, I., and van den Bergh, J. C. (2021). The social multiplier of environmental policy: Application to carbon taxation. *Journal of Environmental Economics and Management*, 105:102396.

Metcalf, G. E. (1999). A distributional analysis of green tax reforms. *National Tax Journal*, 52(4):655–681.

Nakada, M. (2010). Environmental tax reform and growth: Income tax cuts or profits tax reduction. *Environmental and Resource Economics*, 47(4):549–565.

Pearce, D. (1991). The role of carbon taxes in adjusting to global warming. *The Economic Journal*, 101(407):938–948.

Chapter 2

The employment double dividend of environmental tax reforms: exploring the role of agent behaviour and social interaction [1]

2.1 Introduction

With anthropogenic climate change likely exceeding the goals set by the international community in Paris 2015, the need for comprehensive climate policies and their appropriate assessment is more urgent than ever. A revenue-neutral tax shift away from labour and towards carbon dioxide CO_2 emissions, i.e. an environmental tax reform (ETR), is widely considered as such a policy. So far the analysis of ETRs has largely taken place within the domain of public finance and environmental economics relying much on computable general equilibrium (CGE) and macro-econometric models. These tend to focus on representative or average and rational behaviours of consumers and firms.

Here we discuss how considering different types of behaviour, social interactions and heterogeneity of firms and households results in a richer understanding of the mechanisms underlying, and outcomes of, environmental tax reforms. Bounded rationality and non-market social interactions explain how information and innovations diffuse. This is relevant as an ETR is supposed to trigger low-carbon innovations and transitions. Recent studies on ETRs are increasingly paying attention to heterogeneity (e.g. Aubert and Chiroleu-Assouline, 2019; Fullerton and Monti, 2013; Jacobs and

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De Mooij, 2015; Jacobs and van der Ploeg, 2019; Rausch and Schwarz, 2016). This allows, among others, to more accurately account for distributional impacts of the policy. However, heterogeneity is often limited to only one dimension, or where studies go into more detail, there is a disconnect with the macro level.

This study offers a critical review of modelling practices to evaluate the impacts of environmental tax reforms. We examine whether and how a heterogeneous population of boundedly-rational and socially-interacting firms and households can affect the mechanisms of environmental tax reforms, and thus outcomes in terms of relevant economic and environmental indicators. To this end, we synthesise the results from the traditional literature in public finance with insights from behavioural and evolutionary economics, adding observations from labour economics and studies on time use. In the last decade, behavioural economics has come to be seen as particularly important in the context of environmental and energy policies (Allcott and Mullainathan, 2010; Gsottbauer and Van den Bergh, 2011; Shogren and Taylor, 2020). Evolutionary economics is relevant as it can offer insights about how the combination of multiple, heterogeneous agent populations affects climate policies. We offer an explorative study aimed at assessing important model elements or assumptions that deserve investigation. The result can serve as an input to subsequent quantitative model and policy studies focusing on a particular element or assumption in more detail.

In this study, we focus on the so called ‘employment double dividend’ (EDD), denoting a reduction in both environmental pressure (notably CO_2 emissions) and unemployment, given the limited space we have available. The EDD is highly dependent on decision making and thus particularly interesting from a behavioural perspective. It harmonises two goals that are often presented as being conflicting, namely emissions reduction (an environmental goal) and employment (an economic goal). We will evaluate outcomes under distinct sets of behavioural assumptions with respect to these two dividends. Our analysis follows a three-step procedure. First, we identify the main mechanisms through which an ETR is commonly assumed to culminate in an EDD in existing economic models. Second, we critically review central modelling assumptions. Third, we examine double-dividend outcomes for a number of cases combining relevant behaviours, heterogeneity and social interactions of agents, making use of the mechanisms identified in step two to illustrate how policy-makers can benefit from increased realism of economic models.

Following this approach, we find that complementarity between household consumption of leisure and commodities is not necessarily conducive to an employment dividend. The opposite may hold true when one distinguishes between extensive and intensive labour supply, i.e. the number of employed people and the hours worked per employee, respectively. The reason is that increased labour supply through employed individuals can undermine the creation of new jobs. On the firm side, emissions reduction is achieved through costly abatement. If companies are not able to establish product or process innovation, they may face extinction. Notably, equity impacts are influenced by heterogeneity of skills and consumption choices. In addition, time use is relevant, especially for the labour-leisure trade-off, but has been neglected in traditional studies of ETR.

The remainder of the paper is organised as follows. Section 2.2 offers an introduction to the double dividend notion and a roadmap to this study. Section 2.3 sketches the mechanisms of environmental tax reforms and how they relate to an EDD (Section 2.3.1). Section 2.3.2 offers a critical discussion of several key assumptions in the light of different streams of literature and summarises the resulting additional mechanisms we think should receive attention in modelling and policy analysis. Section 2.4 presents the results of a qualitative assessment of different behavioural cases. Section 3.5 discusses the main insights. Section 5.5 concludes.

2.2 Context and approach

2.2.1 The double-dividend notion

Research on environmental tax reforms centres on the double dividend (DD) hypothesis, the notion that one might reap two types of benefits from the policy: one of environmental and the other of economic nature. This combines the concept of Pigouvian taxation, aimed at internalising (environmental) externalities, with the need for distortive taxation in second-best economies.[2] While existing studies tend to represent the first dividend through greenhouse gas or CO_2 emissions reduction, the economic dividend has been approached in various forms. Most authors view it either as enhanced efficiency of the tax system (Bovenberg and De Mooij, 1994) or increased employment (see e.g. Bovenberg and Van der Ploeg, 1998; Bovenberg and Van Der Ploeg, 1998; Koskela and Schöb, 1999; Nielsen et al., 1995). We will concentrate our analysis on the latter, also known as the EDD. While carbon taxes are first and foremost instruments of climate policy, the revenues they are able to generate have triggered much debate about if their use can achieve a second, i.e. economic or welfare, dividend.

A persistent terminological contribution of Goulder (1995) is the distinction between a weak and strong DD. Both take environmental improvement through a tax shift as given. The strong DD notion implies economic improvements compared to a situation with no tax reform. This means an environmental tax could be based on pure efficiency grounds, regardless of its environmental benefits. The weak DD means that there are economic benefits of recycling the pollution tax revenues through cuts in distortionary taxation as compared to returning them to households in a lump-sum fashion, but that there are not necessarily economic improvements compared to the absence of a pollution tax. This hypothesis is supported analytically by Bovenberg and De Mooij

[2] For a more general discussion of Pigouvian taxation in second-best economies see for instance Bovenberg and Goulder (2002).

(1994). Empirically, Bovenberg and Goulder (1996) confirm this result using a numerical model of the United States' economy. Based on a literature review, Ekins and Speck summarise that empirical models typically find a weak double dividend (Ekins and Speck, 2011, p. 37).

Theory and empirics of the double dividend

Most studies show improvement in environmental quality due to pollution taxes. See Bosquet (2000) for an overview of empirical modelling results, or Andersen and Ekins (2009) for an overview of real world cases of ETR in Europe. A recent meta-analysis of ETR simulations using CGE models also concludes that there is consensus about ETRs leading to environmental improvement, while the second dividend remains ambiguous (Freire-González, 2018). Some authors have suggested that environmental benefits may be disappointing under certain conditions (Bosello et al., 2001, p.34 or Bayındır-Upmann and Raith, 2003).

The bulk of the literature in public economics focuses on the existence of the more disputed strong double dividend. It is difficult to draw clear conclusions from analytical models, because as soon as they are extended, for instance with out-of-equilibrium labour markets, there are no longer generally accepted results for a potential strong double dividend. Recycling tax revenues through tax cuts can result in an efficiency dividend only if an initially sub-optimal tax system moves closer to an optimum. Expectedly, many scholars have identified pre-existing distortions, particularly in the labour market, as a crucial condition for the existence of a strong DD (e.g. Bovenberg and Goulder, 1996). The meta-analysis by Freire-González (2018) shows the ambiguity of the results: out of 69 simulations from 40 different studies using CGE models, 55% find evidence for the existence of a strong double dividend and 45% do not. An older study by Patuelli et al. (2005) performs a meta-analysis of 186 simulations (61 studies) including both CGE and macroeconometric models. Their statistical analysis reveals that the type of revenue-recycling and the type of model used both significantly influence the impact of an ETR on gross domestic product and employment.

2.2.2 Conceptual approach

The outcomes of every model depend crucially on its underlying assumptions. The modeller's ideas about the functioning of a policy shape the structure of the model (see Figure 3.1). We perform a synthetic, critical literature review, followed by a qualitative analysis to develop hypotheses about how different behavioural assumptions may affect the outcome of environmental tax reforms. As a first step, we undertake a literature review focused on analytical and numerical models of environmental tax reforms. We highlight key mechanisms used in these models we encountered when reviewing literature from public and environmental economics ('Literature review A'). Each of their assumptions implies certain mechanisms in the model ('Model structure') and affects the model outcomes, as shown in our conceptual framework (Figure 3.1).

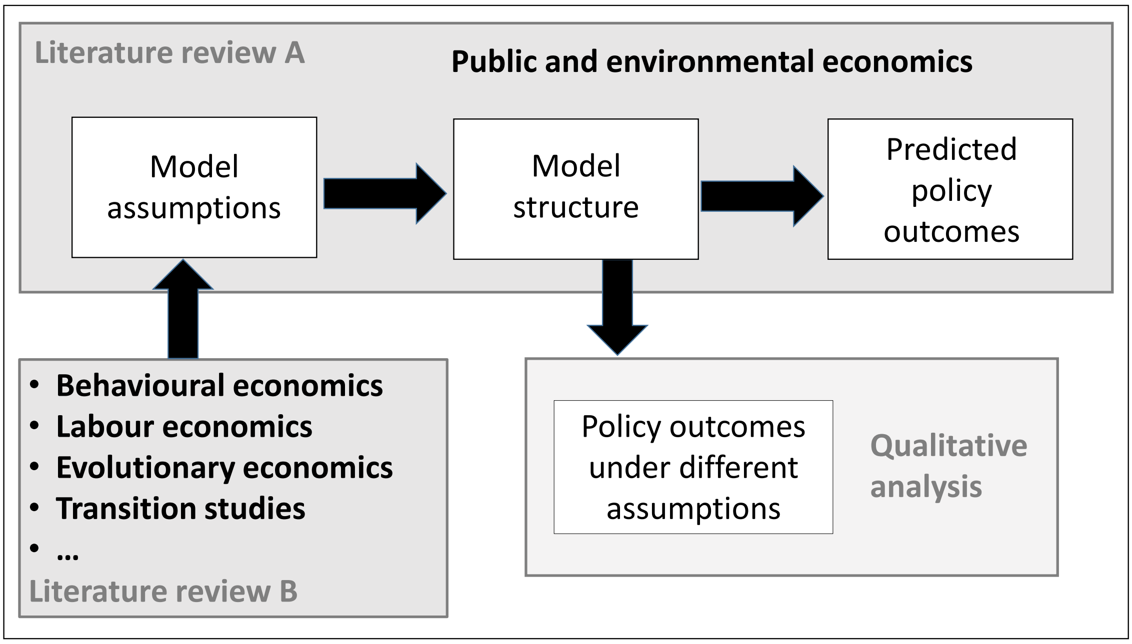

Figure 2.1: Conceptual approach of the study

In a second step, we add insights from other fields, such as behavioural or evolutionary economics ('Literature review B'). We attempt to synthesise the results from our two literature reviews and point out the relevance of interdisciplinary insights. Accounting for the results from Literature review B can affect some of the widely used assumptions for modelling ETRs as well as the mechanisms (Section 2.3.2).

Finally, we hypothesise about the potential impacts of altering these assumptions on the expected outcome of the policy using sets of distinct behavioural cases (Section 2.4). As the literature review follows an explorative approach, the topics are selected in a subjective manner and we do not claim to be comprehensive.

2.3 Synthetic literature review

2.3.1 Basic mechanisms of environmental tax reforms

In most analytical ETR models, firms are assumed to decide about the combination of input factors to maximise their profit. The upper half of Figure 2.2 represents the labour demand side with the effects of the policy on carbon emissions and labour demand. A carbon tax raises the unit cost of carbon emissions (1)[3], mainly through a higher price on production inputs with a high carbon content, such as fossil fuels. The tax cuts enabled through revenue recycling ensure that

[3] The numbers in parentheses in this subsection all refer to arrows in Figure 2.2, e.g. (1) refers to arrow 1.

the unit cost of labour falls (2). Indeed, labour costs may theoretically rise, for instance, due to strong labour unions. For simplicity, we assume the case where tax recycling is strong enough to overcome these opposing effects on labour costs so that the net labour cost falls. In order to lower its costs and maximise profits, the representative firm will try to replace carbon emissions with labour (3 and 4). This is the driving force for innovation that incentivises firms to adjust their production function.

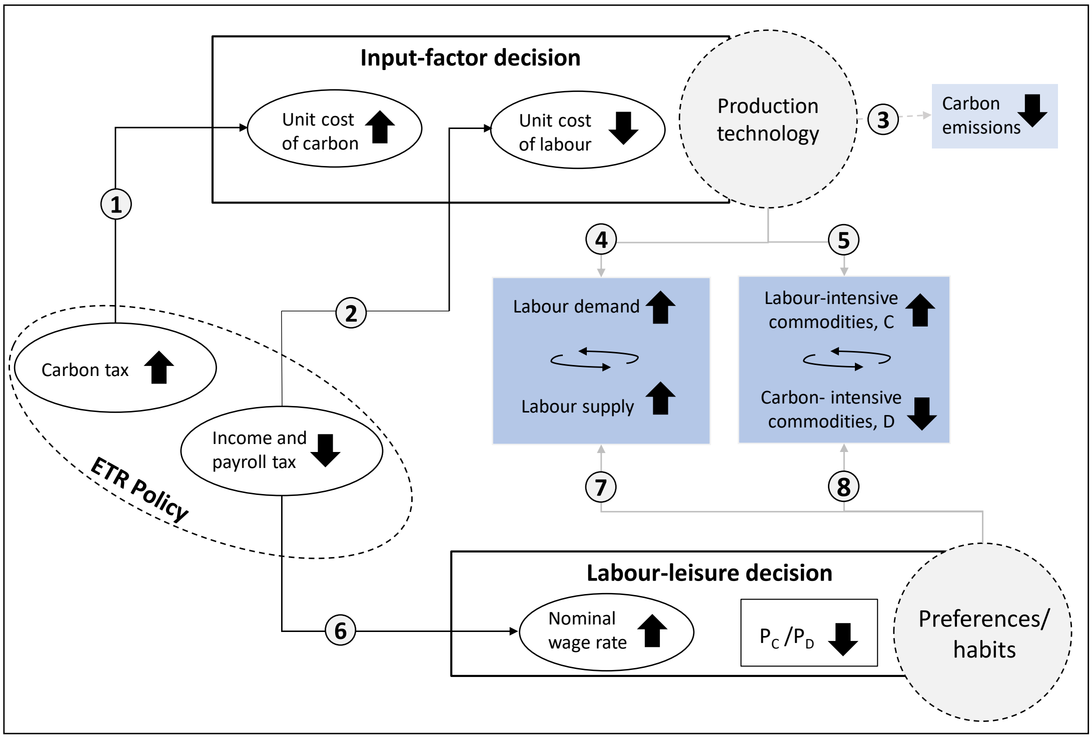

Figure 2.2: Overview of ETR mechanisms

If the benefits of reduced labour costs are split between employers and employees, for instance by recycling revenues through both income and payroll tax cuts, not only will the cost of labour then fall, but also households' after-tax nominal wage rate will increase (6). The latter is expected to promote labour supply because higher nominal wages increase the opportunity cost of leisure (7). The labour-leisure decision is complex, because the relative prices of clean commodities, dirty commodities and leisure all change simultaneously. Carbon-intensive goods become more expensive compared to labour-intensive goods. The exact impacts on the supply and demand of labour, and consumption of clean, i.e. low-carbon, and dirty, i.e. high-carbon, goods cannot be determined ex ante. These depend on the production technology and ability to innovate on the firm side and on preferences and habits on the household side (arrows 3, 4, 5, 7 and 8).

Table 2.1 summarises the main mechanisms found in the literature on ETRs in public economics. Direct effects correspond to price changes triggered by the tax reform. Indirect effects include impacts on household labour-leisure decisions and the firm input-factor decisions. In Table 2.1, as for the remainder of the paper, we assume a general rise in the consumer price index as indicated by empirical studies (Freire-González, 2018).[4] This can be justified based on the current reliance on carbon emissions of virtually all consumption.

Table 2.1: Main mechanisms of ETR including effects on households and firms

	Direct effects	Indirect effects
Household	Nominal wage rate increases (6)	Labour supply increases (7)
	Low-carbon goods relatively cheaper than high-carbon goods (1)	Lower total commodity consumption (8)
		Shift from high-carbon to low-carbon goods (8)
		Increase labour supply (7)
Firm	Unit cost of carbon increases (1)	Reduce carbon emissions (3)
	Unit cost of labour decreases (2)	Labour demand increases (4)
	Labour relatively cheaper than carbon (1,2)	Substitute carbon with labour (3,4)

Note: The numbers in the table relate the effects to the arrows of the mechanisms in Figure 2.2. Column two shows primary price effects and column three the associated changes in demand and supply. Commodities in our analysis are assumed to be either labour- or carbon-intensive (we sometimes refer to the former as 'low-carbon').

2.3.2 Critical assessment of model assumptions

Homothetic preferences

ETR analyses traditionally assume that household preferences are homothetic, implying that a change in income does not affect the share of expenditure for different types of goods (see e.g. Bovenberg and De Mooij, 1997; Parry and Bento, 2000; Babiker et al., 2003). Under these preference assumptions uniform commodity taxes are optimal and lump-sum recycling is most desirable on efficiency grounds (i.e. when ignoring the environmental externality). The model of Babiker et al. (2003) shows that tax cuts can reduce welfare compared to lump-sum recycling of carbon tax revenues. Parry and Bento (2000) employ a static model with homothetic preferences between two pollutive consumption goods, one of which is deductible from the income tax. An income tax reduction, in this case, leads to higher net wages and a shift from tax favoured to non-favoured goods. We would expect an analogous effect if the labour tax cuts induced some kind of shift between dirty and clean consumption goods. This welfare gain (termed 'strong revenue-recycling effect') changes, when the homothetic preference assumption is loosened (Parry and Bento, 2000, p.22).

Homothetic utility functions are a convenient assumption for the tractability of models, but questionable when confronted with empirical evidence. Indeed, the carbon intensity of consumption tends to decrease with rising income. While rich households on average generate higher total emissions per capita, low income households need to assign a larger share of their expenditure to emission-intensive consumption such as energy use for heating or cooking (Büchs and Schnepf,

[4] It should be pointed out that the evidence is limited: only five simulations in Freire-González (2018) include a consumer price index.

2013; Chitnis et al., 2014; Jones and Kammen, 2011; Weber and Matthews, 2008).

Data for the United States used by Sager (2019), for instance, shows that the expenditure share for energy services[5] is higher for low income households than for high income households. According to an analysis of survey data from the United Kingdom (UK), CO_2 emissions are regressive in income for home energy and indirect emissions[6], whereas transport emissions seem to be more 'homothetic' in the sense that they increase almost proportionally with income (Büchs and Schnepf, 2013).

Some recent models of ETR policies incorporate a subsistence level of polluting consumption by assuming Stone-Geary preferences. Aubert and Chiroleu-Assouline (2019) consider a model with heterogeneous workers and imperfect labour markets. Only under specific assumptions, including a low subsistence level of polluting consumption, the initially regressive reform can be rendered Pareto-improving through a non-linear income tax. A study by Jacobs and van der Ploeg (2019) shows that improvements in social welfare are possible without deteriorating inequalities, namely if the government uses lump-sum transfers besides labour taxes. Finally, Klenert and Mattauch (2016) investigate different revenue recycling options, finding that only lump-sum recycling of tax revenues will lead to a progressive result, while all other recycling options render the reform regressive.

Weak separability

Another common, yet difficult assumption is weak separability between leisure and commodity consumption (Babiker et al., 2003; Bovenberg, 1999; Parry and Bento, 2000). It means that households allocate constant fixed expenditure shares to leisure and commodity consumption. This implies that the labour supply decision and consumption choices are independent, i.e. the amount of labour supply does not affect the types of goods and services consumed. A notable exception is Parry (1995), who analyses the optimal pollution tax when leisure and consumption are separable. He concludes that a DD may materialise only if leisure and the polluting consumption good are sufficiently weak substitutes, while most other early models of environmental tax reform find a double dividend under the assumptions of complementarity between leisure and polluting consumption paired with weak separability. A study by West and Williams III (2007) estimates the cross-price elasticity between gasoline and leisure using the United States household expenditure data, finding these goods to be complements. Using a demand system without homotheticity and separability, they show that the optimal gasoline tax rate should be more than one-and-a-half times the rate one would find using a separable utility function. Parry and Bento speculate that in their

[5] Energy services include air travel, electricity, gasoline, heating fuel and natural gas.

[6] Indirect emissions are those not directly emitted by the household, but embodied in consumption of food, recreation or personal care, for instance.

ETR model relaxing the assumption of weak separability would lead to additional welfare gains through positive feedback on labour supply (Parry and Bento, 2000, p.23).

Such feedback effects are highly relevant. While increased income through higher labour supply allows for more budget to be spent on consumption, it also reduces the time budget for leisure. How people spend, and what they consume during their free time, influences the carbon intensity of their consumption. Hence, it is important to account for how commodity consumption of a household responds to changes in time use, for instance when they enter employment. Individuals may substitute time-intensive with time-saving consumption when working hours increase. Goods and services which require processing – be it physical or mental – are likely to be replaced with alternatives that require less time, but are often more carbon-intensive. Examples are replacement of reading with recreational activities that require special equipment or travel such as outdoor sports[7], substitution of raw food ingredients with processed foods, or shifting to faster transportation modes.

The most recent time use survey for Germany, for instance, confirms that eating and drinking outside the house as well as entertainment and culture activities are predominantly performed by employed households, while unemployed individuals are likely to spend more time on food preparation and other activities that take place in their own home, as well as on the job search. Compared to an employed person, an unemployed person on average spends more than twice as much time on preparing meals at home and on household work. Jobless households also undertake more low-emission activities like walking and sleeping (Destatis, 2015). In addition, this data shows that the unemployed invest more time in home-based cultural activities, such as reading, artistic activities or games, whereas employed people have a higher time expenditure for cultural events outside the home. This includes visits to the cinema, theatre or amusement parks (Destatis, 2016). In a time use study for France, De Lauretis et al. (2017) show that high-income households attribute less time to sleep, the least carbon-intensive category. The hypothesis that employed households engage in more carbon-intensive activities is supported also by results of Gough et al. (2011), who find that working households in the UK have higher emissions than unemployed households when other factors, including income, are controlled for. Not only unemployment, but also part-time work may be correlated with low- or high-carbon activity patterns.

It has been recognised that the degree of substitutability between leisure and commodity consumption affects the likelihood of a double dividend to occur. Two examples illustrate this. First, assume that for Household A free time and holiday consumption are complements (negative cross-price elasticity). In this case, a rise in holiday prices reduces the demand for both leisure and

[7] Some studies of time use show that time spent on reading is declining, while household spend more time on sports and outdoor activities (see e.g. Jalas and Juntunen, 2015). The material and emission intensity of these activities is highlighted for instance by Aall et al. (2011) in a study for Norway

holidays, so wage and price changes work in the same direction. The reason is that a price rise for holidays makes leisure time more expensive relative to working time, which promotes labour supply.

The overall effect on labour supply is less clear, if leisure and commodity consumption are substitutes. To illustrate, assume Household B has to commute to work by car, so the cross-price elasticity of leisure and the car is positive. A carbon tax, in this case, raises the price of car use and hence the cost associated with working. While a higher wage promotes labour supply, the increase in commuting costs works in the opposite direction.

The representative household

The typical analytical model for ETR analysis assumes a representative agent with upward sloping labour supply (e.g. Bovenberg, 1999; Bovenberg and De Mooij, 1994). In reality, the goal of the policy is to stimulate employment at the extensive margin, i.e. to create more jobs and reduce unemployment rates, rather than to encourage employed people to work more hours and thus curb intensive labour supply. This distinction is naturally neglected when a representative household is used, although empirical studies show that the wage elasticity of labour supply varies widely between groups of households. According to Fleetwood (2014), the shape and existence of labour supply and demand curves are highly uncertain. The wage elasticity of labour supply for instance is often found to be negative and labour supply curves can be backward-bending instead of upward-sloping. Women typically have relatively higher wage elasticities than men and their intensive and extensive labour supply reactions to wages differ. This is highly relevant for an ETR, because employees who respond to a policy by increasing their working hours may inhibit the creation of new jobs and thus undermine a second dividend.

Recently, Jacobs and De Mooij (2015) suggested that the weak double dividend only holds for models assuming a representative household. The reason is that in these models, no redistribution is necessary or desirable and hence income taxes are distortionary. When households are heterogeneous in skills, however, the distorting effect of labour taxes is balanced out by distributional gains under optimal taxation. In this case, the marginal cost of public funds equals one and cutting distortionary taxes does not imply welfare gains. Deviations in the optimal environmental tax level compared to the Pigouvian rate may still occur, but they will depend on the complementarity between labour and consumption or environmental quality.

Skill heterogeneity is rather established in public economics, and is a key reason for the second-best theory of optimal taxation.[8] The abilities of low- and high-skilled households are commonly approximated through income, warranting the labels low- and high-income households, respectively.

[8]See Lipsey and Lancaster (1956) for the basic idea of the theory of second-best and Diamond and Diamond and Mirrlees (1971a,b) for a first comprehensive application of it to optimal income taxation.

This distinction has been used sparsely in ETR studies in the past, but is gaining momentum lately. The need for including skill heterogeneity is also important with respect to potential discrimination on the labour market.

A second type of heterogeneity we want to consider is pro-environmental preferences. We assume that they contribute to a lower carbon-intensity of consumption, ceteris paribus. As utility is not only derived from leisure and commodity consumption, but also from preserving the natural environment, households exhibiting pro-environmental preferences have a higher willingness to pay for 'green' goods. Hence, an ETR would likely result in different price responses from households with distinct environmental preferences. While we assume for the sake of our analysis that the carbon tax increases awareness about pollution and hence may produce a stronger demand reaction among agents with pro-environmental preferences (*crowding-in*), the monetary incentive itself might cause a *crowding-out effect*, i.e. erode initial intrinsic motivation. Both forms of crowding effects have been shown to be empirically relevant (Frey and Jegen, 2001), with the net effect being uncertain in general. However, this does not affect our general point, which is that demand reactions vary across individuals.

For practical purposes we limit ourselves to these two types of heterogeneity, while noting that other interesting types of household variation exist and have already received some attention. The meaning of spatial heterogeneity between urban and rural populations for tax incidence of the French energy tax reform of 2018, for instance, is addressed using a formal model by Douenne (2020). This study shows that the incidence of energy taxes can depend strongly on the ownership and thus use of capital goods with particular energy-use features, such as cars or homes.

The atomistic household

Consumption choices are not made in a vacuum, but determined by socio-cultural context, that is, influenced by others with possibly different information, resources or preferences. An important example of other-regarding preferences, i.e. preferences influenced by peer behaviour, is status seeking. Discussed already in 1899 by Thorstein Veblen, it is now widely accepted as an important driver of consumption. According to Frank (1985), under status-seeking, consumption and income taxes alleviate existing distortions caused by the under-consumption of non-positional goods, i.e. goods that depend relatively little on how they 'compare with things owned by others' (*ibid*, p.101), to the advantage of positional goods, for which comparison with others is important. In various studies, Norman Ireland shows that a tax on positional – or conspicuous – consumption itself, as well as income taxation can lead to Pareto improvements, which leads him to conclude that over-consumption leads to over-supply of labour (Ireland, 1994, 1998, 2001).

If positional consumption is carbon-intensive compared to non-positional consumption, employment and consumption should be too high and an EDD accordingly more difficult to achieve. The result will also depend on the source of the budget for positional goods: increased labour supply affects both dividends, whereas shifting expenditure between goods will affect mostly the environmental dividend. In a study on the interrelationship of mobility and status, Gössling and Nilsson (2010) argue that institutions like 'frequent flyer' programmes encourage this polluting activity by interlinking flying with social status. If status was instead conveyed through low-carbon commodities or behaviours, it would facilitate the consumption transition that ETR aims to initiate. Examples include college education, reading particular types of literature or consuming ecologically sustainable food (see e.g. Currid-Halkett (2017) for an overview of these new subtle status symbols in the United States).

A number of additional behaviours have been studied in the context of social interaction, including the adoption of energy-efficient technologies based on peer-behaviour (Bollinger and Gillingham, 2012) or attitudes towards climate policies based on political affiliation (Dietz et al., 2007; Tobler et al., 2012). Although we focus on status seeking, our point is to illustrate the general relevance of social, non-market interaction for agent decisions and hence ETR outcomes.

The representative firm

Just as households are heterogeneous, so are firms. The effect of an environmental tax reform will likely differ across different sectors and trigger different strategic reactions. We thus want to introduce two possibly relevant types of heterogeneity on the firm side. As discussed in Section 2.2 an ETR changes the relative and absolute prices of carbon and labour. We account for differences in the ratio of labour to carbon firms use to produce one unit of output. This distinction is relevant if the reactions are non-linear based on this key feature that determines the policy's impact on a company. In an empirical study for Sweden, Brännlund et al. (2014) find that the impact of a carbon tax on environmental performance is almost twice as large for firms in energy-intensive sectors compared to non-energy-intensive companies. Bumpus (2015) carries out interviews with high-level strategic decision makers of energy-intensive firms in British Columbia which reveal that firms with low carbon-intensity see the tax as a compliance cost burden rather than an innovation opportunity.

In addition, a high share of firms in energy-intensive and industrial sectors is extremely environmentally pro-active in climate change mitigation compared to other firms. This last point is the conclusion of a study among 552 companies in Europe and North America (Backman et al., 2017). Not surprisingly, the studies above indicate that emission-intensity seems to determine different reactions of firms to an ETR, justifying this type of heterogeneity.

The second type of firm heterogeneity that will be considered in our analysis is firm size. Empirical evidence points to firm size as a crucial determinant for strategic choices such as innovation, both in response to climate policies, but also other changes in a firm's environment. The results of the aforementioned study also show that large firms are more pro-active than small firms, although this difference is much more significant for Europe than for North America (Backman et al., 2017). Another study by Audia and Greve (2006) investigates the effects of low performance on strategies and risk taking behaviour of small and large firms in the Japanese shipbuilding industry. Their conceptual framework is the shifting-focus model of risk taking which assumes that managers pay attention to more than one reference point. Only small firms switch to less risky strategies when they perform below their aspiration levels in this study. Large firms do not adjust the riskiness in their decision making. The authors explain this by the higher proximity between small firms' survival points and their aspiration levels which makes them more vulnerable to extinction. Together this evidence gives rise to the question whether the impacts on and responses of firms of different size to an ETR will vary. Additionally, firm size is likely correlated with some other key characteristics for strategy choice, such as the age of the company, its market power and political influence and its access to financial capital. The main difference we will assume in our analysis is that small firms may be forced to exit the market more easily than their larger competitors. Another type of heterogeneity that could be relevant for future research is trade-intensity, as Yamazaki (2017) shows in an ex-post empirical evaluation of the environmental tax reform in British Columbia, Canada.

A neglected factor that connects firms and households is skill requirements, because demand for high and low-skilled labour can develop distinctly, depending on firms' strategic reaction to a tax reform. In a meta-analysis of labour demand, covering 151 studies containing 1334 estimates, Lichter et al. (2015) find that the wage elasticity of labour demand is higher for low-skilled workers than for the average worker. It is unclear whether an ETR will lead to a proportional increase in labour demand for high- and low-skilled households. When difference in skills is addressed, it is usually connected to revenue recycling. For instance, Bosello and Carraro (2001) simulate an ETR using a labour market that is disaggregated in terms of skills. They find that recycling revenues to all workers results in a higher employment boost than limiting the transfers to low-skilled workers. The study by Aubert and Chiroleu-Assouline (2019) mentioned earlier introduces the possibility of unemployment among low-skilled workers into a model of ETR through a search and matching approach. Low-skilled labour supply is inelastic, while high-skilled labour is supplied endogenously. Hence low-skilled workers can be employed or unemployed (extensive margin), while high-skilled workers choose the amount of hours they supply (intensive margin). In this case, a progressive labour tax can increase disincentives to work, but could simultaneously increase employment among low-skilled workers. Accounting for these effects highlights trade-offs between efficiency and equity.

Assuming merely a general increase in labour demand discards the fact that low-and high-skilled individuals tend to have different options and that companies will discriminate between skills depending on the strategy they apply.

One strategy of companies is to save energy by replacing machines or energy inputs directly with human labour. In that case, they likely hire low-skilled labour. This may slow down or reverse recent trends in automation in assembly of cars, machines or packaging processes, for instance, but is unlikely to be adopted in all sectors. Another strategy of firms is to hire high-skilled workers who adopt or develop innovations which reduce carbon intensity. In addition, a producer can switch to an entirely new product or service, which may or may not change the skill structure among its employees. A car manufacturer, for example, might switch from automobiles with a combustion engine to electric vehicles because of a tax-induced shift in demand. This restructuring is unlikely to change the skill levels needed in the production process. Firms in different sectors are likely to make different choices among these options under the influence of an ETR and thus the impacts on the labour market are less clear than previously anticipated. One study showing the ambiguity of input elasticities is Fiorito and van den Bergh (2016). Studying volumes and prices of production inputs in the manufacturing sector of seven industrialised countries[9], they find mostly negative cross-price elasticities between labour and energy inputs, indicating complementarity. For Germany, the United Kingdom and the United States however, the corresponding cross-price elasticities are positive, indicating potential to substitute away from carbon emissions.

The atomistic firm

Environmental tax reforms are usually analysed in a typical neoclassical setting with an isolated representative and profit-maximising firm. Cyert et al. (1963)'s book A Behavioral Theory of the Firm lay the foundation for boundedly rational firm behaviour for various disciplines. Evolutionary economics focuses on the role of populations of agents interacting over social networks. This allows for a more disaggregate approach and an emphasis on change processes, which provides important advantages when studying the dynamic pattern of ETR impacts resulting in a major transition away from a high-carbon economy.

Satisficing

We abandon the doctrine of profit-maximisation and replace it with aspiration levels reached through the application of routines. Routines are one of the core concepts of evolutionary economics, defined as repeated sequences of (inter-)action, based on Nelson and Winter (1982). Forming the social analogy to genes in biological evolution, routines carry information, can mutate or

[9] These countries are France, Germany, Italy, Japan, Spain the United Kingdom and the United States.

be adjusted and hence are central to all processes of transition, selection and innovation of firms. Routines make firms inert, but at the same time they create a stable environment for decision making. We will assume that a firm only tries to adjust its routines, if it performs below its aspiration level. The formation of aspiration levels can be considered as a type of satisficing behaviour. Based on the theory of structural inertia we will assume that routine use makes large firms more inert than smaller firms. Regarding the ETR we can assume that routines slow down the transition process compared to profit-maximising firms. The use of aspiration levels means that only firms which are negatively affected by the tax reform, i.e. perform below their aspiration levels, will react to the policy with structural changes. For small firms routines imply an extra pressure for preventing extinction, because any delay in reaction to the policy can threaten their existence and lead to market exit.

Innovation through social interaction

On the firm side social interaction between different companies is especially important with respect to the search and innovation process. Basically, there are two types of interaction: imitation of competitors and cooperation. According to Rycroft (2007), the dominant assertion is that network-based partnerships are at the core of faster innovation. That is because these collaborations can deal better with the variety and uncertainty of a globalised economy. While this hypothesis is not uncontested, for our analysis we will assume that interaction between firms increases the speed of innovation diffusion and thus the potential of a double dividend to occur. Furthermore, social interaction should particularly improve the survival rates of small firms in a changing environment as they can lower their search costs.

On the perception of taxes

The idea that tax-induced price changes generate distinct demand responses when compared with equivalent market price fluctuations has been termed *tax salience* (Rivers and Schaufele, 2015, p.24). While distinct reactions to taxes and other price changes are not necessarily relevant for analytical models, different demand elasticities are highly relevant for numerical analyses of environmental tax reforms. Rivers and Schaufele (2015) study the effects of the ETR in British Columbia and find that under a tax rate of \$25/tCO2e the demand reduction induced by the local carbon tax is four times as strong as suggested by price elasticities. A study by Brännlund et al. (2014) observes a similar 'signalling' effect of carbon taxes in the context of the Swedish ETR. Analysing micro-level firm data, they discover that the tax reduces the carbon intensity of production significantly more than an equivalent change in fuel prices. The effects of carbon taxes compared to other price changes are illustrated in Figure 2.3.

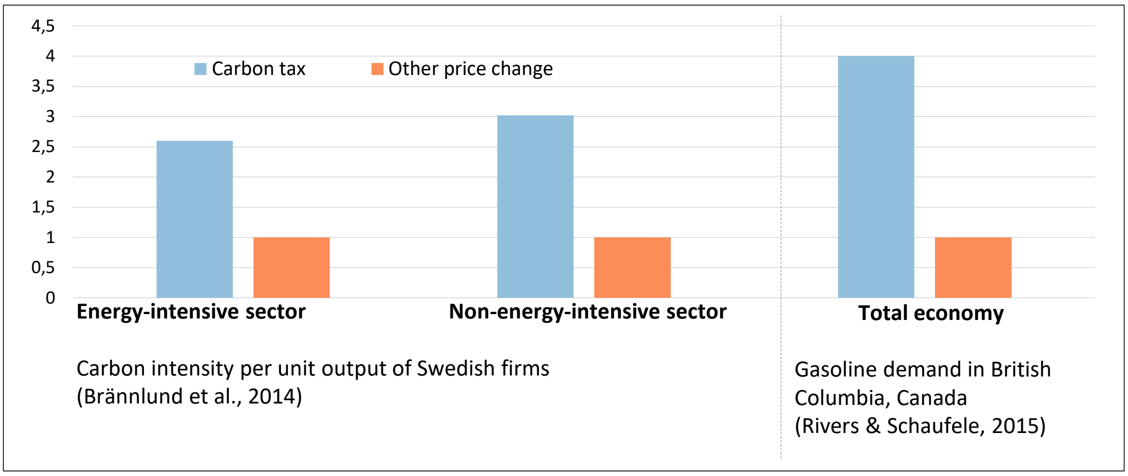

Figure 2.3: Reactions to carbon dioxide taxes versus other price changes

Traditional models do not account for salience or signalling effects, but tax changes are expected to have the same effect as equivalent price changes. Two early studies of tax salience performed by Chetty et al. (2009) and Finkelstein (2009) focus on households in the United States. Whereas Chetty et al. show that higher salience of taxes amplifies the demand reaction, Finkelstein's results indicate that lower tax salience reduces the demand elasticity.

In an empirical investigation of the demand reaction to gasoline taxes, Li et al. (2014) use household- and state-level data from the United States. Compared to tax-inclusive gasoline prices a gasoline tax induces a stronger demand reaction for fuel consumption as well as vehicle choice. A recent study by Andersson (2019) estimates the effect of the Swedish carbon tax on emissions using a quasi-experimental approach with a synthetic control of comparable OECD countries. It finds a carbon tax elasticity of fuel consumption three times larger than the price elasticity. While the drivers of these results cannot easily be determined, all the previous studies indicate that some form of tax salience or signalling effect seems to apply to both households and firms.

The impacts of changing assumptions on model mechanisms

We have laid out the main mechanisms through which an EDD is expected to be realised in Section 2.3.1 and discussed a number of key assumptions in Section 2.3.2. While potential impacts of different assumptions about agent behaviour on the double dividend will be analysed in Section 2.4, implications for the channels through which the policy works, i.e. for the model structure, are summarised in Table 2.2. The left columns are identical with Table 2.1 whereas the column on the far right adds more subtle insights about mechanisms we identified in Section 2.3.2.

Questioning homothetic preferences implies that one needs to expect different demand reactions by high and low income households following an ETR (i). How households use their free time when their employment situation changes is a crucial determinant of the carbon intensity of their

Table 2.2: Effects of key assumptions on mechanisms of an ETR

	Traditional ETR mechanisms		Additional ETR mechanisms
	Direct effects	**Indirect effects**	**New indirect effects**
Household	Nominal wage rate increases	Labour supply increases	Extensive labour supply increases (iii)
			Intensive labour supply may rise or fall (iii)
	Low-carbon goods relatively cheaper than high-carbon goods	Lower total commodity consumption	Only possible for high income households (subsistence limit) (i)
		Shift from high-carbon to low-carbon goods	Will require more time: lower intensive labour supply (ii) (iii)
		Increase labour supply	Increase in intensive labour supply (iii)
Firm	Unit cost of carbon increases	Reduce carbon emissions	Increase carbon efficiency at the margin (e.g. optimisation of internal processes or shift to renewable energy sources).
	Unit cost of labour decreases	Labour demand increases	Hire more workers proportionally
	Labour relatively cheaper than carbon	Substitute carbon with labour	Direct emission replacement through low-skilled labour (iv)
			Indirect emission replacement by high-skilled labour (iv)

Note: Extension of Table 2.1 by the right column based on our literature review. New mechanisms become relevant when (i) moving away from homothetic preferences, (ii) dropping weak separability between leisure and consumption, (iii) distinguishing extensive and intensive labour supply, and (iv) allowing for distinct demand for low- and high-skilled labour.

consumption and hence the effectiveness of the tax reform (ii). The distinction between labour supply at the intensive and extensive margin, respectively, introduces an additional threat to the employment dividend (iii). Workers who increase their hours of labour may prohibit the creation of new jobs. Last but not least, the strategic choice of firms in reaction to an ETR will determine whether demand for high- or low-skilled labour increases (iv). We will now turn to developing concrete behavioural cases with distinct assumptions about households.

2.4 Analysis of distinct behavioural cases

In this section, we will apply the insights presented in Section 2.3.2 to the mechanisms of environmental tax reforms in the form of eight different behavioural cases. Outcomes will be evaluated in terms of the likelihood of an EDD, i.e. CO_2 emission reduction and an increased employment rate. We will evaluate each agent along the mechanisms identified in Tables 2.1 and 2.2. As the price change for carbon- and labour-intensive goods is expected to work in opposite directions, it is unclear what exactly will happen to the overall commodity price index (CPI). To simplify the analysis, we will restrict it to the case where the price index rises because almost all commodities will get more expensive, i.e. a rise in CPI. We perform a qualitative analysis of household reactions to ETR first and after that analyse the different firm cases. Due to uncertainty about the magnitude of the effects, we abstain from combining the two.

2.4.1 The household decision

We consider four different household cases:

1. HH-RR – one rational representative household (like traditional models: baseline)
2. HH-RH – rational, but heterogeneous households (differing in skills and pro-environmental preferences)
3. HH-BRH – boundedly rational (prone to salience effects) and heterogeneous households
4. HH-SH – Socially interacting (through status-seeking) and heterogeneous households

Household heterogeneity here always refers to the variety in skills and pro-environmental preferences discussed before. Rationality is a disputed concept. Here we refer to a rational household as an atomistic utility maximiser with complete information and perfect foresight. Table 2.3 presents the potential for a double dividend to occur across the four cases. The detailed steps of the analysis can be found in the appendix.

Table 2.3: Double dividend potential of an ETR for different household cases

		HH-RR Fully rational	HH-RH Heterogeneity	HH-BRH Tax salience	HH-SH Status-seeking
Representative HH		+/++			
Skills	Pro-environ. preferences				
Low	No		- - -/0	0/0	- - -/-
	Yes		- -/0	-/+	-/-
High	No		0/+++	+/++++	- -/-
	Yes		++/+++	++/++++	+++/++

Note: The four columns show the results of the four household cases. Values left of the '/' symbol refer to the environmental dividend, those on the right to the employment dividend. '+' indicates better chances for a dividend to occur, '-' lower chances, and '0' an unclear effect. The signs are the result of the various mechanisms from Tables 1 and 2, working in the same or opposing directions and thus more signs mean a higher likelihood of an effect.

To construct our baseline HH-RR case similar to traditional ETR analyses, we only use the channels in Table 2.1. An increase in nominal wage rates is expected to lead to an increase in labour supply and thus promote the second dividend. If commodity consumption and leisure are complements, a rise in commodity prices will strengthen both dividends, because price and wage rise promote labour supply and reduce commodity consumption. If leisure and commodities are substitutable, on the other hand, higher commodity prices still imply lower consumption, but also lower labour supply, thus strengthening the first dividend but weakening the second. The relative potential for a double dividend is represented in the upper left cell of Table 2.3. The dividends should not be interpreted as dividends received by a certain type of household, but rather display how different types of households contribute to an overall double dividend.

Column 2 displays the HH-RH case where households are rational, but heterogeneous in skills and preferences. The potential for a DD varies widely between the high- and low-skilled groups.

There are three main reasons for this pattern. First, the tax reform may stimulate intensive labour supply and thus inhibit the creation of new jobs. Second and in connection to the criticism brought forward by Bayındır-Upmann and Raith (2003), higher employment almost certainly will translate into higher consumption, especially for low-income groups. Third, the consumption of low-income households has been shown to be more carbon-intensive as they spend a larger share of their income on food, housing and energy (see Section 2.3.1). This is why we see negative impacts for the environment in these cells of Table 2.3. For high-skilled households the chances are better for both dividends because the substitutability between their commodity consumption and leisure actually leads to a decrease in intensive labour supply, thus promoting the EDD, rather than preventing it. Additionally, the higher distance to subsistence levels and decreasing marginal returns to consumption open up space for consumption reduction.

For the behavioural case with tax salience (HH-BRH, column 3) we see a similar pattern as for the second case, but overall the likelihood of a DD seems larger. This result roots in the amplified demand reduction in response to a tax, compared to a price change. One might argue that this is only a short-term effect and in the long term the remaining income will be spent. What we have assumed here is that real income falls and households rather reduce their demand for commodities instead of increasing their labour supply to sustain their former consumption level. In this case, there will not be any remaining income even in the long run.

The last household case HH-SH assumes socially interacting heterogeneous agents and is displayed in the last column of Table 2.3. Here we see strong deviations from the former results. A crucial difference in the analysis is that we assume all households, including high-skilled individuals with pro-environmental preferences, to increase their labour supply at both margins. This is based on the analyses of Ireland (1994, 1998, 2001), and the assumption that status-seeking leads to oversupply of labour. One could criticise that status-seeking does not increase labour supply, but rather shifts resources from non-positional to positional goods (see e.g. Frank, 1985). From an environmental perspective however, status-seeking is problematic because it creates externalities. The essential question is how status is conveyed. We assume that the mainstream status symbols are very carbon-intensive, which is responsible for the negative results with respect to environmental benefits. The weak chances for an EDD stem from the strong increase in intensive labour supply. Pro-environmental preferences can make a difference in this case as they may promote the environmental dividend through low-carbon status symbols which are currently rather a niche than the norm in Western societies.

In general, we see that the DD potential is higher for high-skilled groups, in particular those with green preferences. More thought should be put into the distinction between commodities as leisure complements versus substitutes. This difference mainly stems from the time required to consume certain goods and thus there is a strong link between the labour decision and the consumption decision as mentioned earlier. Due to the distinction between intensive and extensive labour supply, our analysis further suggests a reversed pattern of influence of leisure complements on the EDD than is normally suggested. Since household heterogeneity and different behaviours can have a tremendous effect on the DD outcome, a more detailed analysis of ETR best devote attention to these.

2.4.2 The firm decision

Regarding the firm side, we also distinguish between four cases:

1. F-RR – one rational, i.e. profit-maximising, representative firm (baseline)
2. F-RH – profit-maximising heterogeneous (in size and labour-to-carbon ratio) firms
3. F-BRH – heterogeneous firms satisficing with aspiration levels and routines
4. F-SH – socially interacting heterogeneous firms

In the F-RR case, the ETR will lead to an increase in carbon efficiency which is positive for emission reduction, i.e. the environmental dividend. So is the second mechanism on the firm side: increased cost of carbon and lower labour cost lead to replacement of carbon with labour. This shift is expected not only to improve the environment, but also to have a positive impact on employment by raising labour demand (++/+). This baseline case is again based on the mechanisms from Table 2.1 and the result is shown in the upper left cell in Table 2.4.

Table 2.4: Double dividend potential of an ETR for different firm cases

		F-RR Profit-maximiser	F-RH Heterogeneity	F-BRH Satisficing	F-SH Social innovation
Representative firm		++/+			
Energy-intensity	Firm size				
High	Small		+++/0	++++/-	+++/+
	Large		+++/+	++/+	+++/+
Low	Small		++/+	0/(+)	++/+
	Large		++/+	++/+	++/+

Note: The four columns show the results of the four firm cases. Values left of the '/' symbol refer to the environmental dividend,those on the right to the employment dividend. '+' indicates better chances for a dividend to occur, '-' lower chances and '0' that the direction is unclear. Each mechanism (from Tables 1 or 2) is the source of a sign, working in the same or opposite direction, so more signs indicate a higher likelihood of an effect.

Similar to the household analysis, cases 2–4 are evaluated using Table 2.2, i.e. we use one additional mechanism[10]: market exit or extinction of firms. Overall the results suggest that the outlook is more positive for the environmental dividend than for employment. There is not much

[10] Table 2.2 also includes different strategies for hiring low versus high-skilled labour. We only pay limited attention to these demand variations here, because we have no reliable information of strategy structures with respect to this point.

variation across the different cases within the types of firms, and the environmental benefits from energy-intensive industries are always at least as high as from the labour-intensive sectors. The latter result is not surprising. As energy-intensive firms bear the largest share of the costs of the tax reform, they supposedly react strongest. In addition, they probably have the largest abatement potential.

Behavioural Case 2, F-RH, considers heterogeneity of profit-maximising firms in terms of size and carbon-intensity.We disregard the possibility of renewable energy use here, because this strategy will not have any impact on labour demand, and also refer to energy-intensity. The results show similar emission reductions among all energy-intensive companies. For large firms these reductions are the result of efficient abatement due to economies of scale and innovation, whereas small energy-intensive firms are exposed to frequent extinction resulting in emission reduction. This comes at the cost of losing jobs among smaller companies and thus lowers the potential for the second dividend.

Case 3 introduces decision making based on aspiration levels and routines (satisficing). The results are shown in the third column of Table 2.4. In this case, the transition process slows down for all types of companies, because routine-based decision making introduces inertia. The greatest difference compared to case 2 pertains to small labour-intensive firms. The reason is that they are likely to exceed their original aspiration levels after an ETR and thus will not introduce any changes at all – based on the idea that firms react mostly when they underperform. While automation tends to cause job losses in small labour-intensive companies, such as in the service industry, labour cost reductions due to an ETR could help to protect jobs in these sectors. That is why we added the (+). The negative impact on employment for small energy-intensive firms stems from the increased extinction risk they are exposed to when they use routines compared to a traditional profit-maximiser.

Social innovation which allows for cooperation among firms and imitation of competitors coins the fourth behavioural case, displayed in the last column. Our assumption is that these conditions will facilitate a faster innovation process and hence a more rapid transition away from carbon emissions. Extinction rates of small firms in energy-intensive industries are lowered, because they can copy successful competitors or economise on their resource use through cooperation. This has a positive impact on the second dividend. Even small labour-intensive firms may contribute to environmental improvements in this case because they can imitate emission reducing techniques from their larger competitors without investing a lot in R&D. A downside may be a lower demand for high-skilled labour in the R&D process.

In sum, we take away three main insights from the firm analysis. Although we expect similar emission reductions within the distinct types of firms across our cases, the mechanisms to arrive there differ. For some of the companies, abatement comes about through market exit rather than innovation. This holds particularly when comparing small carbon-intensive firms with and without social innovation. Second, the different cases mainly affect the speed of transition, a factor that is neglected in traditional analyses. Third, as our examples of replacement of human labour through automation or lower research personnel demand in the case social innovation show, the different cases may affect different types of jobs in a separate manner. It is thus likely that they will affect the distributional outcome of an ETR. These factors should be included in the policy analysis in order to get a comprehensive picture, including equity impacts.

2.5 Discussion

2.5.1 Results of behavioural cases

The qualitative analysis of four behavioural cases was performed for households and firms, respectively. Even if some of the results for the double dividend potential are similar to the baseline rational representative agent case (RR), the underlying mechanisms of an ETR and its side effects are much more differentiated than is usually considered. The distinction between extensive and intensive labour supply reversed our understanding of the impact of the substitutability between commodity consumption and leisure on employment. If leisure and consumption are complements, an ETR may increase the supply of labour at the intensive margin, which will inhibit, rather than support the creation of new jobs (employment dividend). Tax salience has a positive effect on emission reduction and on employment creation among the high-skilled labour force, whereas status-seeking may pose a serious threat to both dividends if positional consumption causes oversupply of labour.

The analysis of firms shows higher potential for the environmental dividend in all cases compared to the baseline, and particularly in emission-intensive sectors. Adding the possibility of market exit threatens the second dividend for small firms. Emission reduction may be realised through extinction at the cost of losing jobs, rather than through innovation. We expect routine-based decision making and social innovation to affect the speed of the transition of the economy. Routines are likely to slow down the transition to a low-carbon economy while non-market interactions can accelerate it. Allowing firms to cooperate and imitate successful competitors probably decreases the risk of extinction for small firms as well. Finally, the shift from labour to carbon can happen through direct replacement of carbon through human energy or through innovation in carbon productivity as a result of R&D. The latter channel is most likely the more important one and will require high-skilled labour. Although an ETR may have the potential to temporarily slow down current digitalisation and automation trends, the outcome in terms of labour demand is likely to be skewed between high and low-skilled households. These different impacts for different segments of the population need to be considered in policy evaluations.

The assessment was based on a combination of a critical literature review and additional own argumentations that integrated insights from different fields. It should be seen as a starting point for behavioural modelling approaches to studying the environmental and socio-economic impacts of ETRs. Given the broad scope, we had to be selective and focus on important cases, rather than offer an exhaustive treatment of potential behavioural assumptions and implications. Because of the qualitative nature of our analysis, we further had to neglect the interaction of behavioural cases, especially between firms and households. To more systematically address this, specific formal models are required, which can benefit from our explorative insights. Agent-based modelling is one technique to overcome restrictive assumptions of traditional models and to comprehensively incorporate relevant boundedly-rational and socially-interactive behaviours as well as heterogeneity in the context of ETR. These models have seen considerable application to climate policy (Castro et al., 2020), but not been systematically used to answer questions about a DD of an ETR. In future work, we intend to elaborate some of the ideas exposed here along these lines.

2.5.2 Limitations

Only the basic channels of one type of dividend – the EDD – were considered, while it should be noted that other definitions of the economic dividend and other channels exist and have been studied. Examples include additional production factors (e.g. Bovenberg and Van der Ploeg, 1998), informal labour markets (e.g. Goulder, 2013; Bento et al., 2018 or health benefits (e.g. Williams III, 2002). Our analysis concentrates on the impacts on labour and commodity markets. Based on empirical studies, we assumed a general rise in the consumer price index. We also assumed that benefits of the tax reform are split between employers and employees and we considered only labour and carbon as input factors to production. Altering these central assumption will likely affect our results. Finally, as we do not employ a model we cannot draw any conclusion about optimal tax policy. The point we want to make is that some of the typical assumptions should be re-evaluated with respect to empirical evidence and future models should be built with the necessary flexibility in mind.

2.6 Conclusions

The aim of this study was to examine whether and how particular deviations in behaviour from rational representative agents affect the mechanisms set in motion by an environmental tax reform (ETR). To that end, a literature review was performed to identify the effects of the policy on labour and commodity markets. Adding insights from literatures on time use, labour studies and behavioural and evolutionary economics has provided insights about extending existing models of ETR with other relevant mechanisms (Table 2.2).

One important result is that complementarity between leisure and commodity consumption does not have to be favourable for an employment dividend. Considering the distinction between extensive and intensive labour supply, the opposite can be true if increased labour supply through employed individuals undermines the creation of new jobs. Allowing for the possibility of firm bankruptcy can further threaten the employment dividend. Heterogeneity in skills and consumption choices affects the equity impacts of an ETR through tax incidence and potential shifts in labour demand. With respect to the labour-leisure trade-off, more attention should be paid to the use of time as a resource, in addition to income.

Although we did not focus on the magnitude of the various behaviours on the outcome of an ETR, our analysis has revealed the importance of deviations from assumptions of traditional models. Not only do they have the potential to affect the outcome in terms of the double dividend – as already shown by recent ETR studies – but they actually require us to consider additional mechanisms through which the tax reform unfolds and re-think the way we model the environmental and socio-economic impacts of an ETR.

References

Aall, C., Klepp, I. G., Engeset, A. B., Skuland, S. E., and Støa, E. (2011). Leisure and sustainable development in Norway: part of the solution and the problem. *Leisure Studies*, 30(4):453–476.

Allcott, H. and Mullainathan, S. (2010). Behavior and energy policy. *Science*, 327(5970):1204–1205.

Andersen, M. S. and Ekins, P. (2009). *Carbon-energy taxation: lessons from Europe*. OUP Oxford.

Andersson, J. J. (2019). Carbon taxes and CO_2 emissions: Sweden as a case study. *American Economic Journal: Economic Policy*, 11(4):1–30.

Aubert, D. and Chiroleu-Assouline, M. (2019). Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82.

Audia, P. G. and Greve, H. R. (2006). Less likely to fail: Low performance, firm size, and factory expansion in the shipbuilding industry. *Management science*, 52(1):83–94.

Babiker, M. H., Metcalf, G. E., and Reilly, J. (2003). Tax distortions and global climate policy. *Journal of Environmental Economics and Management*, 46(2):269–287.

Backman, C. A., Verbeke, A., and Schulz, R. A. (2017). The drivers of corporate climate change strategies and public policy: a new resource-based view perspective. *Business & Society*, 56(4):545–575.

Bayındır-Upmann, T. and Raith, M. G. (2003). Should high-tax countries pursue revenue-neutral ecological tax reforms? *European Economic Review*, 47(1):41–60.

Bento, A. M., Jacobsen, M. R., and Liu, A. A. (2018). Environmental policy in the presence of an informal sector. *Journal of Environmental Economics and Management*, 90:61–77.

Bollinger, B. and Gillingham, K. (2012). Peer effects in the diffusion of solar photovoltaic panels. *Marketing Science*, 31(6):900–912.

Bosello, F. and Carraro, C. (2001). Recycling energy taxes: impacts on a disaggregated labour market. *Energy Economics*, 23(5):569–594.

Bosello, F., Carraro, C., and Galeotti, M. (2001). The double dividend issue: modeling strategies and empirical findings. *Environment and Development Economics*, 6(1):9–45.

Bosquet, B. (2000). Environmental tax reform: does it work? A survey of the empirical evidence. *Ecological economics*, 34(1):19–32.

Bovenberg, A. (1999). Green tax reforms and the double dividend: an updated reader's guide. *International tax and public finance*, 6(3):421–443.

Bovenberg, A. and Van der Ploeg, F. (1998). Consequences of environmental tax reform for unemployment and welfare. *Environmental and Resource Economics*, 12(2):137–150.

Bovenberg, A. L. and De Mooij, R. A. (1994). Environmental levies and distortionary taxation. *The American Economic Review*, 84(4):1085–1089.

Bovenberg, A. L. and De Mooij, R. A. (1997). Environmental tax reform and endogenous growth. *Journal of Public Economics*, 63(2):207–237.

Bovenberg, A. L. and Goulder, L. H. (2002). Environmental taxation and regulation. In *Handbook of public economics*, volume 3, pages 1471–1545. Elsevier.

Bovenberg, A. L. and Van Der Ploeg, F. (1998). Tax reform, structural unemployment and the environment. *Scandinavian Journal of Economics*, 100(3):593–610.

Bovenberg, L. and Goulder, L. H. (1996). Optimal environmental taxation in the presence of other taxes: general equilibrium analyses. *American Economic Review*, 86:985–1000.

Brännlund, R., Lundgren, T., and Marklund, P.-O. (2014). Carbon intensity in production and the effects of climate policy—evidence from Swedish industry. *Energy Policy*, 67:844–857.

Büchs, M. and Schnepf, S. V. (2013). Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO_2 emissions. *Ecological Economics*, 90:114–123.

Bumpus, A. G. (2015). Firm responses to a carbon price: corporate decision making under British Columbia's carbon tax. *Climate policy*, 15(4):475–493.

Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., and van den Bergh, J. (2020). A review of agent-based modeling of climate-energy policy. *Wiley Interdisciplinary Reviews: Climate Change*, 11(4):e647.

Chetty, R., Looney, A., and Kroft, K. (2009). Salience and taxation: Theory and evidence. *American economic review*, 99(4):1145–77.

Chitnis, M., Sorrell, S., Druckman, A., Firth, S. K., and Jackson, T. (2014). Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. *Ecological Economics*, 106:12–32.

Currid-Halkett, E. (2017). *The Sum of Small Things*. Princeton University Press.

Cyert, R. M., March, J. G., et al. (1963). *A behavioral theory of the firm*, volume 2. Englewood Cliffs, NJ.

De Lauretis, S., Ghersi, F., and Cayla, J.-M. (2017). Energy consumption and activity patterns: an analysis extended to total time and energy use for French households. *Applied Energy*, 206:634–648.

Destatis (2015). Zeitverwendungserhebung. Aktivitäten in Stunden und Minuten für ausgewählte Personengruppen.

Destatis (2016). Zeitverwendung für Kultur und kulturelle Aktivitäten in Deutschland. Sonderauswertung der Zeitverwendungserhebung.

Diamond, P. A. and Mirrlees, J. A. (1971a). Optimal taxation and public production i: Production efficiency. *The American Economic Review*, 61(1):8–27.

Diamond, P. A. and Mirrlees, J. A. (1971b). Optimal taxation and public production ii: Tax rules. *The American Economic Review*, 61(3):261–278.

Dietz, T., Dan, A., and Shwom, R. (2007). Support for climate change policy: Social psychological and social structural influences. *Rural Sociology*, 72(2):185–214.

Douenne, T. (2020). The vertical and horizontal distributive effects of energy taxes: A case study of a French policy. *The Energy Journal*, 41(3).

Ekins, P. and Speck, S. (2011). *Environmental tax reform (ETR): a policy for green growth*. Oxford University Press.

Finkelstein, A. (2009). E-ztax: Tax salience and tax rates. *The Quarterly Journal of Economics*, 124(3):969–1010.

Fiorito, G. and van den Bergh, J. C. (2016). Capital-energy substitution in manufacturing for seven OECD countries: learning about potential effects of climate policy and peak oil. *Energy Efficiency*, 9(1):49–65.

Fleetwood, S. (2014). Do labour supply and demand curves exist? *Cambridge Journal of Economics*, 38(5):1087–1113.

Frank, R. H. (1985). The demand for unobservable and other nonpositional goods. *The American Economic Review*, 75(1):101–116.

Freire-González, J. (2018). Environmental taxation and the double dividend hypothesis in cge modelling literature: A critical review. *Journal of Policy Modeling*, 40(1):194–223.

Frey, B. S. and Jegen, R. (2001). Motivation crowding theory. *Journal of Economic Surveys*, 15(5):589–611.

Fullerton, D. and Monti, H. (2013). Can pollution tax rebates protect low-wage earners? *Journal of Environmental Economics and Management*, 66(3):539–553.

Gössling, S. and Nilsson, J. H. (2010). Frequent flyer programmes and the reproduction of aeromobility. *Environment and Planning A*, 42(1):241–252.

Gough, I., Abdallah, S., Johnson, V., Ryan-Collins, J., and Smith, C. (2011). The distribution of total greenhouse gas emissions by households in the uk, and some implications for social policy. *LSE STICERD Research Paper No. CASE152*.

Goulder, L. H. (1995). Environmental taxation and the double dividend: a reader's guide. *International Tax and Public Finance*, 2(2):157–183.

Goulder, L. H. (2013). Climate change policy's interactions with the tax system. *Energy Economics*, 40:S3–S11.

Gsottbauer, E. and Van den Bergh, J. C. (2011). Environmental policy theory given bounded rationality and other-regarding preferences. *Environmental and Resource Economics*, 49(2):263–304.

Ireland, N. J. (1994). On limiting the market for status signals. *Journal of Public Economics*, 53(1):91–110.

Ireland, N. J. (1998). Status-seeking, income taxation and efficiency. *Journal of Public Economics*, 70(1):99–113.

Ireland, N. J. (2001). Optimal income tax in the presence of status effects. *Journal of Public Economics*, 81(2):193–212.

Jacobs, B. and De Mooij, R. A. (2015). Pigou meets Mirrlees: On the irrelevance of tax distortions for the second-best Pigouvian tax. *Journal of Environmental Economics and Management*, 71:90–108.

Jacobs, B. and van der Ploeg, F. (2019). Redistribution and pollution taxes with non-linear Engel curves. *Journal of Environmental Economics and Management*, 95:198–226.

Jalas, M. and Juntunen, J. K. (2015). Energy intensive lifestyles: Time use, the activity patterns of consumers, and related energy demands in Finland. *Ecological Economics*, 113:51–59.

Jones, C. M. and Kammen, D. M. (2011). Quantifying carbon footprint reduction opportunities for us households and communities. *Environmental Science & Technology*, 45(9):4088–4095.

Klenert, D. and Mattauch, L. (2016). How to make a carbon tax reform progressive: The role of subsistence consumption. *Economics Letters*, 138:100–103.

Koskela, E. and Schöb, R. (1999). Alleviating unemployment:: The case for green tax reforms. *European Economic Review*, 43(9):1723–1746.

Li, S., Linn, J., and Muehlegger, E. (2014). Gasoline taxes and consumer behavior. *American Economic Journal: Economic Policy*, 6(4):302–42.

Lichter, A., Peichl, A., and Siegloch, S. (2015). The own-wage elasticity of labor demand: A meta-regression analysis. *European Economic Review*, 80:94–119.

Lipsey, R. G. and Lancaster, K. (1956). The general theory of second best. *The review of economic studies*, 24(1):11–32.

Nelson, R. R. and Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. Harvard University Press.

Nielsen, S. B., Pedersen, L. H., and Sørensen, P. B. (1995). Environmental policy, pollution, unemployment, and endogenous growth. *International Tax and Public Finance*, 2(2):185–205.

Parry, I. W. (1995). Pollution taxes and revenue recycling. *Journal of Environmental Economics and Management*, 29(3):S64–S77.

Parry, I. W. and Bento, A. M. (2000). Tax deductions, environmental policy, and the “double dividend” hypothesis. *Journal of Environmental Economics and Management*, 39(1):67–96.

Patuelli, R., Nijkamp, P., and Pels, E. (2005). Environmental tax reform and the double dividend: A meta-analytical performance assessment. *Ecological economics*, 55(4):564–583.

Rausch, S. and Schwarz, G. A. (2016). Household heterogeneity, aggregation, and the distributional impacts of environmental taxes. *Journal of Public Economics*, 138:43–57.

Rivers, N. and Schaufele, B. (2015). Salience of carbon taxes in the gasoline market. *Journal of Environmental Economics and Management*, 74:23–36.

Rycroft, R. W. (2007). Does cooperation absorb complexity? Innovation networks and the speed and spread of complex technological innovation. *Technological forecasting and social change*, 74(5):565–578.

Sager, L. (2019). Income inequality and carbon consumption: Evidence from environmental Engel curves. *Energy Economics*, 84:104507.

Shogren, J. F. and Taylor, L. O. (2020). On behavioral-environmental economics. *Review of Environmental Economics and Policy*.

Tobler, C., Visschers, V. H., and Siegrist, M. (2012). Addressing climate change: Determinants of consumers' willingness to act and to support policy measures. *Journal of Environmental Psychology*, 32(3):197–207.

Weber, C. L. and Matthews, H. S. (2008). Quantifying the global and distributional aspects of American household carbon footprint. *Ecological economics*, 66(2-3):379–391.

West, S. E. and Williams III, R. C. (2007). Optimal taxation and cross-price effects on labor supply: estimates of the optimal gas tax. *Journal of public Economics*, 91(3-4):593–617.

Williams III, R. C. (2002). Environmental tax interactions when pollution affects health or productivity. *Journal of Environmental Economics and Management*, 44(2):261–270.

Yamazaki, A. (2017). Jobs and climate policy: Evidence from British Columbia's revenue-neutral carbon tax. *Journal of Environmental Economics and Management*, 83:197–216.

Appendix 2.A Detailed analysis of behavioural cases

Table 2.5: Potential of an ETR to create a double dividend under various behavioural cases

			ETR POLICY			ANALYSIS			DD		ANALYSIS			DD		ANALYSIS			DD
Households	**Insights from the literature in public economics (Section 3.1) ⇒**				**Case 1: HH-RR – Representative and rational**														
			w	↑	1	Labour supply (L_S)	↑	(-)/+	+/++										
			p	↑	2	Complements (C_C)	↑	+/+											
			p	↑	3	Substitutes (C_S)	↓	0/0											
	Results from Section 4.1				**Case 2: HH-RH – Heterogeneity**					**Case 3: HH-BRH – Tax salience**					**Case 4: HH-SH – Status seeking**				
	Low skills (Upward-sloping L_S, C and V are complements)	No env. pref.	w	↑	4	Extensive L_S	↑	-/+	—/0	16	Extensive L_S	↑	-/+	0/0	28	Extensive Ls	↑	-/+	—/-
					5	Intensive L_S	↑	-/-		17	Intensive L_S	↑	0/-		29	Intensive L_S	↑	-/-	
			p	↑	6	Demand for C_C	↓	-/0		18	Demand for C_C	↓	+/0		30	Demand for C_C	=	-/-	
		Env. pref.	w	↑	7	Extensive L_S	↑	-/+	–/0	19	Extensive L_S	↑	-/+	-/+	31	Extensive L_S	↑	-/+	-/-
					8	Intensive L_S	↑	-/-		20	Intensive L_S	↑	-/-		32	Intensive L_S	↑	-/-	
			p	↑	9	Demand for C_C	↓	0/0		21	Demand for C_C	↓	+/+		33	Demand for C_C	=	-/-	
	High skills (Backward-bending L_S, C and V are substitutes)	No env. pref.	w	↑	10	Extensive L_S	↑	-/+	0/+++	22	Extensive L_S	↑	-/+	+/++++	34	Extensive L_S	↑	-/+	–/-
					11	Intensive L_S	=	0/+		23	Intensive L_S	=	0/+		35	Intensive L_S	↑	-/-	
			p	↑	12	Demand for C_S	↓	+/+		24	Demand for C_S	↓	++/++		36	Demand for C_S	=	0/-	
		Env pref	w	↑	13	Extensive L_S	↑	0/+	++/+++	25	Extensive L_S	↑	0/+	++/++++	37	Extensive L_S	↑	0/+	+++/++
					14	Intensive L_S	↓	0/+		26	Intensive L_S	↓	0/+		38	Intensive L_S	↑	+/-	
			p	↑	15	Demand for C_S	↓	++/+		27	Demand for C_S	↓	++/++		39	Demand for C_S	↓	++/++	
Firms	**Insights from the literature in public economics (Section 3.1) ⇒**				**Case 1: F-RR – Representative and rational**														
			MC_C	↑	1	Carbon efficiency	↑	+/0	++/+										
			MC_L	↓	2	Substitution	↑	+/+											
	Results from Section 4.2				**Case 2: F-RH – Heterogeneity**					**Case 3: F-BRH – Satisficing**					**Case 4: F-SH – Social innovation**				
	Energy-intensive (low L/C ratio)	small	MC_C	↑	3	Carbon efficiency	↑	+/0	+++/0	17	Carbon efficiency	↑	+/0	++++/-	31	Carbon efficiency	↑	++/0	+++/+
			MC_C	↑	4	Extinction	↑	+/-		18	Extinction	↑	++/–		32	Extinction	=	0/0	
			MC_C	↑	5	Substitution	↑	+/+		19	Substitution	↑	+/+		33	Substitution	↑	+/+	
			MC_L	↓	6	Substitution				20	Substitution				34	Substitution			
		large	MC_C	↑	7	Carbon efficiency	↑	+/0	+++/+	21	Carbon efficiency	↑	+/0	++/+	35	Carbon efficiency	↑	+/0	+++/+
			MC_C	↑	8	Substitution	↑	++/+		22	Substitution	↑	+/+		36	Substitution	↑	++/+	
			MC_L	↓	9	Substitution				23	Substitution				37	Substitution			
	Non-energy-intensive (high L/C ratio)	small	MC_C	↑	10	Carbon efficiency	↑	+/0	++/+	24	Carbon efficiency	=	0/0	0/(+)	38	Carbon efficiency	↑	+/0	++/+
			MC_C	↑	11	Extinction	=	0/0		25	Extinction	=	0/0		39	Extinction	=	0/0	
			MC_C	↑	12	Substitution	↑	+/+		26	Substitution	=	0/(+)		40	Substitution	↑	+/+	
			MC_L	↓	13	Substitution				27	Substitution				41	Substitution			
		large	MC_C	↑	14	Carbon efficiency	↑	+/0	++/+	28	Carbon efficiency	↑	+/0	++/+	42	Carbon efficiency	↑	+/0	++/+
			MC_C	↑	15	Substitution	↑	+/+		29	Substitution	↑	+/+		43	Substitution	↑	+/+	
			MC_L	↓	16	Substitution				30	Substitution				44	Substitution			

Households

Behavioural case 1: HH-RRA – Representative and rational households

1. A higher wage increases labour supply [/+], which is good for the second dividend but potentially threatens the first [(-)/].
2. Commodity demand goes down after prices rise. This promotes the first dividend [+/]. If leisure and commodity consumption are complements it promotes the second dividend as well [/+].
3. If they are substitutes there is a trade-off between leisure and consumption reduction. The effects on the first and the second dividend are unclear [0/0].

Behavioural case 2: HH-RHA – Heterogeneity

Low-skilled households

4. A higher wage rate promotes extensive labour supply and thus the second dividend [/+]. We assume that increased labour supply and lower complement consumption will lead to a shift towards substitute commodities. Since commodities that are substitutable for leisure are assumed to be time-saving, they likely have a higher carbon intensity [-/].
5. A higher wage also promotes intensive labour supply for low income households as they are close to subsistence consumption. This is bad for the second dividend because it prevents the creation of new jobs [/-]. For consumption and the first dividend the argument from above holds [-/].
6. The commodity price rise induces a demand reduction. We assume that low income households with no environmental preferences replace these commodities with time-saving and high-carbon alternatives, thus leading to an overall negative impact on the environment. The impact of increased labour supply is unclear [-/0]. At the extensive margin it promotes the second dividend, at the intensive margin it prevents it.
7. A higher wage rate promotes extensive labour supply and thus the second dividend [/+] (like in 4.). Although these households have pro-environmental preferences we assume them to attach more weight to work-related high energy consumption due to their low income and absolute level of consumption [-/].
8. Intensive labour supply rises too, following the higher wage rate [/-] (like in 5.) and we assume a similar increase in substitute consumption [-/].
9. The consumption of complements falls after the price rise, but we assume that it is to some extent replaced by low-carbon substitutes (such as services) rather than high-carbon substitutes, based on HHs pro-environmental preferences. The impact is not expected to be strong though [0/]. Again, the impact of increased labour supply is unclear [/0].

High-skilled households

10. A higher wage rate promotes extensive labour supply for high-skilled workers as well and with it higher consumption of high carbon-leisure substitutes, such as private vehicles for commuting. This means a negative impact on environmental quality and a positive employment impact [-/+].
11. Intensive labour demand is assumed to stay the same for high income HHs without environmental preferences, because they are further away from subsistence consumption and experience decreasing returns to additional income. This gives room for the second dividend as there is no competition between employed and unemployed people to fulfil labour demand. We assume that consumption patterns stay the same [0/+].
12. The price increase for commodities depresses demand. As high income households are assumed to substitute commodities and leisure, the labour supply falls as well, again promoting the second dividend rather than weakening it [+/+].
13. Extensive labour supply increases, but HHs with pro-environmental preferences are assumed to use their income for less carbon intensive consumption [0/+].
14. Intensive labour supply falls following a wage increase. HHs with pro-environmental preferences derive additional utility from preserving the natural environment and thus attach a lower weight to utility from income. This reduction is an additional stimulation for the second dividend by creating more labour demand, we assume they only reduce intensive labour supply so far as to sustain their old consumption habits [0/+].
15. The increased commodity price lowers the demand for substitute commodities, which likely improves the environment [+/]. This reduction will bring about an increased demand for leisure, e.g. to have the time to consume rather time-intensive but low-carbon goods, and thus a reduction in labour supply. As, however this reduction can be expected to come from already employed people, it would free up jobs for the unemployed and thus be – again contrary to the traditional argument – promoting the second dividend, rather than inhibiting it [/+].

Behavioural case 3: HH-BRHA – Tax salience

Low-skilled households

16. No change compared to case 2. The reason is that low income households are already very attentive to prices even without tax salience.
17. No change compared to case 2. See above.
18. The commodity price increase reduces commodity consumption, which is complementary to leisure and hence promotes labour supply. This favours the second dividend if it is at the extensive margin but threatens it when at the intensive margin. Thus the overall effect remains unclear [/0]. Due to the over-reaction to the tax we assume an overall reduction in carbon-intensive consumption, leading to a positive effect on the environment [+/].
19. No change compared to case 2.
20. No change compared to case 2.
21. Again, the price rise in leisure complements lowers intensive labour supply, thus promoting the second dividend. Due to tax salience, we assume that commodities are not replaced by other consumption [+/+].

High-skilled households

28.-29. No change compared to case 2.

30. The price rise induces a demand reduction of leisure substitutes, leading to lower (intensive) labour supply. We assume the demand reduction to be stronger under tax salience [++/++].

31.-32. No change compared to case 2.

33. Again, based on the literature we assume that the demand reduction will be stronger than without tax salience, improving the probability of both dividends compared to the second (and first) case [++/++].

Behavioural case 4: HH-SHA – Status seeking

Low-skilled households

34. No change compared to case 2.
35. Intensive labour supply increases following a higher wage rate, preventing the second dividend. As individuals are seeking status, they use their additional income to consume mainstream positional goods, which are typically high-carbon goods substitutable to leisure, such as cars, bigger houses, carbon-intensive holidays, etc. [-/-].
36. The price increase lowers consumption of complements, but they are likely to be replaced by time-saving high carbon consumption, made necessary and financed through increased labour supply [-/-].
37. No change compared to case 2.
38. Intensive labour supply increases after a rise of the wage rate, inhibiting the second dividend. Although the pro-environmental preferences make households use additional income for supposedly 'green' status goods it still increases their overall material consumption [-/-]. That is because they cannot afford the free time necessary to truly consume green, as that is time-intensive.
39. The price change leads to a lower consumption of leisure complements, supporting (intensive) labour supply. In the status-seeking case, where low-skilled green households try to imitate high-skilled green households, they will try hard to consume low carbon leisure substitutes to position themselves. This yields environmental improvements but still inhibits the creation of new jobs through increased intensive labour supply [+/-].

High-skilled households

40. No change compared to case 2.
41. When agents are status seeking even when their income is high the wage rate will lead to increased labour supply at the intensive margin to sustain or expand consumption. This works against both dividends [-/-].
42. The price rise induces a demand reduction for commodities. As they are mostly leisure substitutes, this fosters an increase in labour supply. When positional consumption matters we assume that consumption levels will at least stay the same and be financed through increased labour supply if necessary [0/-].
43. No change compared to case 2.
44. Some status seeking agents may be expected to increase their intensive labour supply even when they have a high income and environmental preferences. This can weaken the second dividend. However, any additional income is expected to be used for lowering carbon consumption, which is the status symbol of the 'green elite', e.g. local and seasonal products, and thus be beneficial for the environment [+/-].

45. The demand for time-saving leisure substitutes will go down following a price increase favouring more time-intensive consumption and hence lower intensive labour supply. For rich households with pro-environmental preferences this could be a return to truly green time-intensive status symbols [++/++].

Firms

Behavioural case 1: F-RRA – Representative and rational

1. A higher marginal cost of carbon emissions incentivises firms to improve their carbon efficiency. This improves the environment but has not necessarily an impact on labour [+/0].
2. The lower cost of labour together with the higher cost of carbon incentivises a shift from labour to carbon which supports both dividends [+/+].

Behavioural case 2: F-RHA – Heterogeneity

All firms

3–16. The policy induces the same changes across all firms: the higher price of carbon leads to efficiency improvements, and together with the lower unit cost of labour induces a factor shift. This always leads to positive effects for the environment and employment. A new channel exists that is particularly relevant for small firms: extinction (or market exit). The higher cost of carbon will put pressure especially on small energy-intensive firms who operate close to their survival point. This increased extinction risk threatens the employment dividend. We assume that the environmental impact of large energy-intensive firms is stronger than that of small competitors or labour-intensive firms.

Behavioural case 3: F-BRHA – Satisficing

Energy-intensive firms

17. No change compared to case 2.
18. Extinction rates of small firms are higher under routine use and aspiration levels, because transitions happen slower and managers choose from selection of all existing options only.
19. Higher cost of carbon induces factor shift, but slower.
20. Lower cost of labour induces factor shift, but slower.

21.-23. No change compared to case 2, but process expected to be slower.

Non-energy-intensive firms

24. Small labour-intensive firms who require little energy will potentially perform above their aspiration levels and will thus not adjust (except maybe in the very long run). No effect on employment or emissions [0/0].
25. The probability of extinction for small labour-intensive firms does not change. Their costs probably get lower, but so do those of their competitors. No impact on either of the dividends.
26. Substitution of carbon through use of labour is probably limited in these industries. However, current trends in robotics may be slowed down, leading to a temporary protection of jobs. This favours the second dividend. The impacts for the first dividend are probably negligible [0/(+)]. The robotic argument steps a bit outside our analysis and is thus put in parentheses.
27. See 10.

28.-30. No change compared to case 2, but process expected to be slower.

Behavioural case 4: F-SHA – Social innovation

Energy-intensive firms

31. Higher cost of carbon leads to efficiency increases. Under social innovation the speed of transition is higher than in case 2 [++/0].
32. The extinction rates of small firms are probably not increasing significantly if they can cooperate and/or imitate successful competitors. Thus there will be no big extinction impact on either of the dividends [0/0].
33. Substitution will also happen faster than in the atomistic case 2. The impact on labour may be stronger because of the transition speed, or weaker because of less labour requirements due to cooperation. Thus we are not changing it compared to case 2 [++/+].
34. See 3.
35. Efficiency improvements motivated by a higher unit cost of carbon are assumed to happen faster.
36. Substitution of carbon with labour is assumed to happen faster.
37. See 6.

Non-energy-intensive firms

38. If small labour-intensive firms are able to observe and learn from their competitors, efficiency improvements seem more likely in this sector. This promotes environmental benefits [+/0]. The result is the same as in the case 2, where firms maximise profit, but the reason is different. Here the firms evolve through learning to arrive at a similar result.
39. The extinction rate for small labour-intensive companies should not become higher, as in case 2 because they can imitate the best practice of others, hence improving the chances for an EDD.
40. No change compared to case 2. But again, result driven by non-market cooperation instead of profit maximisation.
41. See 10.
42. Result as in case 2. Firms come close to profit-maximisation over time through social learning and copying their competitors' behaviours.
43. Substitution is also happening, because in large companies – even if they are labour-intensive – monitoring of routines and practices will lead to a factor shift. However, total emission reduction is probably small, but research in efficiency improvements creates jobs, which promotes the second dividend.
44. See 13.

Chapter 3

How work patterns affect leisure activities and energy consumption: A time-use analysis for Finland and France [1]

3.1 Introduction

Existing policies in the context of the climate crisis often aim at reducing greenhouse gas (GHG) emissions, while fostering or redistributing employment. Examples include work time reduction (Schor, 2005; Jackson and Victor, 2011) or environmental tax reforms with revenue recycling through labour taxes (Bovenberg, 1999). Researchers frequently refer to multiple dividends of these policies, such as the 'double dividend' of environmental and economic (efficiency) goals of tax reforms, or the 'triple dividends' of work time reduction: "enhanced ecological sustainability, social equity and life satisfaction" (Buhl and Acosta, 2016).

Such comprehensive policies affect multiple aspects of human life and behaviour, including work and consumption decisions, work-life balance and societal arrangements, such as labour organisation. Yet quantitative approaches to assess policies for sustainability have often been limited to monetary effects (Minx and Baiocchi, 2009). Lately, more attention has been paid to the impacts of leisure time allocation and its environmental impact when work hours change (see e.g. Buhl and Acosta, 2016; Nässén and Larsson, 2015). These studies include time budgets into their analysis,

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but they tend to focus on average effect across populations. Doing so neglects potentially different impacts of work time on leisure activities and thus conceals which sub-groups should be targeted by policy interventions to effectively reduce energy demand.

In this study we perform an activity-based time-use analysis of the impact of work time on leisure activities and energy use for Finland and France. Our focus is on the heterogeneity of activity patterns and their impact on energy use, especially with respect to individuals' general availability of leisure time, which we measure through a respondent's employment status (part-time or full-time). Four research questions (RQs) are guiding our analysis:

(i) Which activities are undertaken more or less when comparing different levels of work time?

(ii) How do people change duration of their leisure activities in response to changing work time?

(iii) Does a person's employment status moderate the allocation of leisure time?

(iv) How does the energy use of leisure activities change in response to different work hours?

To answer these questions, we estimate a number of econometric models relating work time, leisure activities and energy use, using national-level data for Finland and France. The context of the analysis is thus one of two wealthy European societies with relatively high rankings in energy use per capita. Total primary energy use per person for instance was 6924.7 and 3692.0 kg of oil equivalent in 2015 in Finland and France, respectively (Bank, 2015). There are however important cultural, geographic and socio-economic differences between the two countries. The sub-arctic Finnish climate explains higher energy consumption, typical for the Nordic countries, compared to the French temperate climate.

There are also some important differences with respect to work patterns. According to its Fifth European Working Conditions Survey (Eurofound, 2012), dual-earner households are very common in both countries, but the share of households with a male 'breadwinner' is more dominant in France and the share of female 'breadwinners' is higher in Finland. Part-time contracts are much more usual among French women compared to men, whereas the gender shares are rather balanced in Finland (Eurofound, 2012). From the fourth survey wave we also know that autonomy over working time is higher in Finland than in France (Parent-Thirion et al., 2007). While our empirical analysis does not include societal or labour market institutions, results should be interpreted against this geographical, cultural and institutional backdrop.

The remainder of the paper is organised as follows. Section 3.2 offers an overview of the relevant literature and places our study therein. Data and methodology are explained in Section 5.3. Section 3.4 presents the results of our econometric analysis, which are discussed in Section 3.5. Section 5.5 concludes.

3.2 Literature review

Time use has played an increasing role in recent undertakings to comprehend the environmental impact of household behaviour. The fact that both human well-being and emissions are not the sole and instantaneous result of the act of purchasing, but also arise from the use of goods and services over time, has led to the evaluation of environmental impacts of different activities per unit of time. Such studies typically combine national time-use diaries with the respective household expenditure surveys to calculate energy use or emissions per hour of an activity (Schipper et al., 1989; Jalas, 2002, 2005; Druckman et al., 2012; Jalas and Juntunen, 2015; Smetschka et al., 2019; Yu et al., 2019). The recent studies in particular highlight the importance of differentiating between various household types, because energy intensities of one activity can vary widely with context (think, for instance, about different modes of transportation).

The relationship between work patterns and environmental impacts has been addressed especially in the context of work time reduction scenarios (see Antal et al., 2020 for a systematic literature review). A number of empirical studies have been carried out with a macroeconomic focus, comparing average work time and environmental impact (Schor, 2005), energy use (Rosnick and Weisbrot, 2007) or carbon footprints (Knight et al., 2013) across countries. These studies typically find that an increase in average work time by 1% leads to an increase in energy use or emissions by>1%. This effect is mostly attributed to income effects.

A scenario analysis of five potential work time reduction policies focusing on full-time employees in the United Kingdom (UK) finds a large variation in mitigation potential (King and van den Bergh, 2017). Employee time use is one of many elements included in this analysis, alongside income effects and changes in business activities. It is assumed that additional leisure time is utilised consistent with current time-use patterns.

Recently, a strand of literature has emerged that uses a microeconomic framing to analyse the marginal effects of a work time reduction on energy use and emissions (Nässén and Larsson, 2015) or on the triple dividend mentioned above (Buhl and Acosta, 2016). Nässén and Larsson (*ibid.*) calculate the average income elasticity of energy use for the Swedish population. The study connects expenditure and time-use data to distinguish between income and time effects. The results indicate a positive relationship between energy use and income and a negative relationship between energy use and work time. As the time effect (shift in activities) is weaker than the income effect, a 1% reduction in work time leads to a drop in energy use by 0.7%. Households with one or more unemployed or retired adult members are excluded from this sample. An open question remains why the reduction in emissions the study finds is lower than the estimates of most macroeconomic studies.

Buhl and Acosta (2016) apply a similar framework of marginal effects to German data. They look at the causal effects of work time reduction on activities using two waves from the German Socio-Economic Panel survey. Their mixed methods approach also includes interviews with people who have reduced their work hours. Analysing the triple dividend of work time reduction, they also disregard unemployed individuals when drawing conclusions about social equity impacts of work time reduction. While the study indicates potential quadratic relationships between work time and undertaking particular activities, these results are not pursued any further.

So far household heterogeneity in terms of employment patterns as well as energy intensity per time unit of an activity remains neglected in these studies, especially given that other authors have highlighted the need for assessing differences across household groups. The environmental impact of particular activities can vary widely depending on factors such as income, age, household size, urban form or employment status (Jalas and Juntunen, 2015; Gough et al., 2011; De Lauretis et al., 2017; Wiedenhofer et al., 2018). Particularly interesting from our perspective is a study by Gough et al. (2011), which investigates drivers of GHG emissions in the United Kingdom based on the UK Expenditure and Food survey. While income is identified as the main driver, employment status alone explains 7% of variation in per capita emissions in their model. Although their findings indicate no significant difference between full-time employees and either part-time employees or retirees, unemployed individuals or self-employed people have significantly lower or higher emissions than full-time workers, respectively. Moreover, the study investigates differences in work time and occupation, without applying any time-use data which may help to explain how differences in emissions come about.

Finally, the change in marginal duration of different activities is interesting. By analogy with the better known 'marginal propensity to consume', Buhl and Acosta (2016) call this change 'marginal propensity to time use'. Intuitively, it makes sense that the reaction in time use given an additional work hour is different for someone with a 40-hour work week, compared to someone with a 20-hour work week. The impacts of a change in working time at the margin are highly relevant to policy design: a non-linear 'marginal propensity to time use' would imply varying effectiveness for energy use reduction depending on the target group of a policy.

Our study builds on microeconomic approaches to analysing energy use through activities as in Buhl and Acosta (2016) and Nässén and Larsson (2015). Our contribution involves a focus on heterogeneity of individuals in terms of (a) differentiating between effects on occupational groups with varying degrees of available non-work time (i.e. part-time versus full-time employees), (b) using different energy intensities for different household types, and (c) allowing for non-linear relationships between work and other activities. Finally, we extend the investigation of the relationship between work hours and non-work activities from Sweden and Germany in previous studies to Finland and France, motivated by data availability. Using harmonised activity data for two countries allows us to compare discrepancies in time allocation in different contexts.

3.3 Data and method

3.3.1 Conceptual framework

In order to address the four research questions posed previously, three sets of regression models are estimated (Figure 3.1). Model 1 (M1) involves regressing the duration of each non-work activity on average daily work hours, which allows us to investigate how leisure time is allocated by respondents with various levels of work. This can be thought of as a form of time budgeting: an increase (decrease) in work time will necessarily lead to a decrease (increase) in other activities. Model 2 (M2) investigates how the relative share of time in various activities changes with work

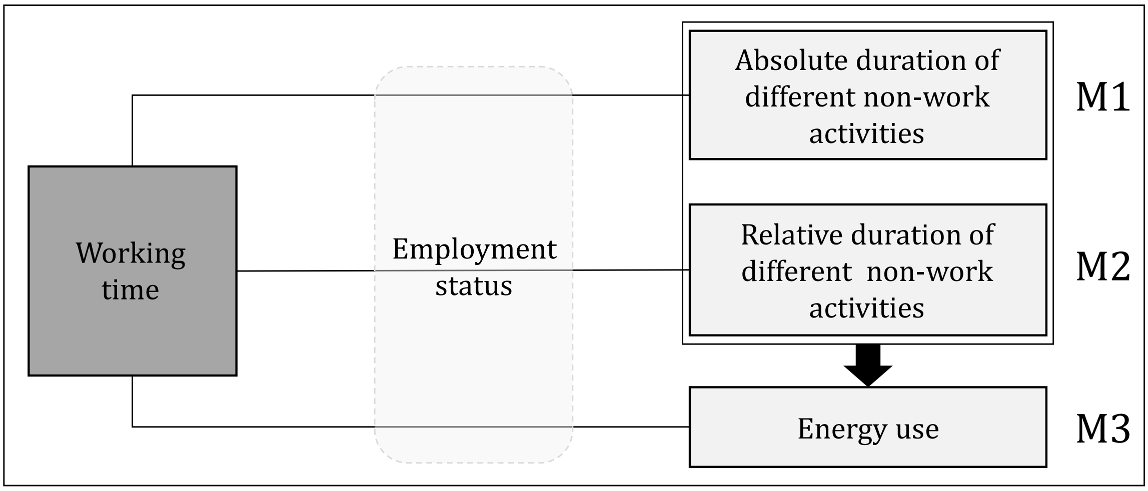


Figure 3.1: Conceptual framework

Note: Dark grey left box indicates the main independent variable and the light grey boxes on the right dependent variables of models M1-M3. The employment status is expected to moderate the relationship between work and leisure.

time. These two steps address research questions (i) through (iii), which all concern the relationship between duration of paid work and other activities[2]. The relevant independent variables are work time (RQ i), squared work time (RQ ii), and an interaction term between work time and the employment status of a person. The latter allows to assess differences in effects between full-time and part-time employees (RQ iii). The categorisation is taken directly from the time use data base. Students and people who are retired, seeking work, or looking after family, but who work at least some hours, are also coded as working part-time.

Regression Model 3 (M3) estimates the relationship between energy use during leisure time and working hours (RQ iv). Energy use is calculated based on the leisure activities performed by

[2]Note that there is not one model per research question, but rather certain model coefficients relate to specific questions.

each household type. We use a consumption-based approach to calculate total energy use and energy-intensity (per hour) during leisure time. The term 'energy intensity' appears throughout this paper to refer to energy use per unit of time, for one specific or all non-work activities. To obtain energy use, we multiply energy intensity factors per hour of each activity with the time spent on these activities. This means no energy use is allocated to time spent at work, which is in line with previous studies (as mentioned in Section 3.2).

3.3.2 Data sources

Our main data source is the Multinational Time Use Survey (MTUS) (Gershuny, 2013). It collects and harmonises time diary data from various countries. The analysis is performed using the most recent available time-use data sets, which are from 2009 for both countries. This data is originally collected in a diary format, where participants fill in information on their activities in 10-minute-intervals during up to two sample days, mostly one weekday and one weekend day. Reported activities are then coded and provided in 24 different categories. In each regression model we use observation weights provided by the MTUS data base ('PROPWT'), in order to ensure a representative sample in terms of days, gender and age (weekend days are over-represented, for instance)[3].

To link activity patterns to energy use, we are building on the energy intensities of different activities estimated by Jalas and Juntunen (2015) for Finland and De Lauretis et al. (2017) for France. We assign 23 of the 24 activity categories (excluding paid work) from the MTUS data set to the categories used in those studies. Appendix 3.A offers an overview of the activity categories and the classifications used by Jalas and Juntunen (*ibid.*) and De Laretis et al. (*ibid.*) for calculating hourly energy intensities. Both papers group households according to age, civil and family status, i.e. whether someone lives with a partner and whether they have children[4]. This household typology implicitly covers some other important factors, such as disposable income (typically lower for older people) or scale effects (reflected in household size).

While the time-use categories are identical for both countries, an important difference that prohibits the two countries' energy use to be directly comparable, is that the Finnish data includes embodied energy used during the production of goods), whereas the data for France is limited to direct energy use (fuel, electricity, etc.). Both studies calculate energy use by combining expenditure survey data with time-use data. De Lauretis et al. (*ibid.*) additionally use housing, appliance and mobility surveys. For Finland, monetary values are converted into energy demand using environmentally-extended input–output tables with a four-digit COICOP classification of

[3]For details on the construction of the weights, we refer the interested reader to the description section of the PROPWT variable on the MTUS website: https://www.mtusdata.org/.

[4]The categories for both countries are 'Single < 65' , 'Couple, reference person < 65' , 'Single parent', 'Couple with children', 'Couple, reference person > 65' , and for France in addition 'Other'.

goods. For France, energy expenses are converted using energy prices specific to energy form and household type. Appendix 3.E indicates the average energy intensity for each activity group from the two reference studies. We refer the interested reader to the two original studies (Jalas and Juntunen, 2015; De Lauretis et al., 2017) for further details on energy intensity calculations. Keeping these differences in mind, our results on energy use should be seen as outcomes pertaining to different contexts, rather than as a direct country comparison.

3.3.3 Data preparation

The time-use data is provided through two data bases which contain different variables from the same survey (MTUS and MTUS-X). Thus, we first have to merge these data sets based on observations' unique identifiers. As we are mainly interested in the workforce, we then discard observations of minors below the age of 16 years and unemployed people, as well as observations which were neither categorised as full-time employed or part-time employed and who had not indicated any work on the sample day or during the week preceding the sample day. Lastly, we delete observations which lack information on weekly work hours, control variables or activities throughout the day or which cannot be assigned to any of the household types used in the underlying energy use studies. The remaining sample size is 3,291 observations for Finland and 10,983 for France. The observations represent person-days and the sample covers 1,756 individuals (1,223 households) for Finland and 6,976 individuals (5,218 households) for France.

We test whether the data preparation leads to a biased sample by performing a Kolmogorov-Smirnov test (with the null hypothesis that the two samples are drawn from the same distribution) and a Wilcox rank sum test (equivalent to the Mann-Whitney test, with the null hypothesis that the two distributions differ in terms of a location shift, see Appendix 3.C). The results for Finland show that household size, age, education level and employment status of missing observations differ from the overall sample, with differences in means between the final sample and eliminated values being equal to 6.78% (household size), 3,76% (age), 1.4% (education) and 3.53% (employment status). People in the remaining sample tend to live in slightly larger households, are less educated, older and more often full-time employed. For the French sample, the observations we delete are also slightly older and from larger households. The deleted observations include more educated, female, full-time and higher-income respondents. These differences in means are all within 5%, except for employment status (13.01%). Table 3.1 offers an overview of the main variables in the final data set.

Table 3.1: Summary of main variables by country and occupational status

	Finland			France		
	Full-time (N=2957)	Part-time (N=334)	Overall (N=3291)	Full-time (N=914)	Part-time (N=1837)	Overall (N=10983)
Average daily work time (WT)*						
Mean (SD)	5.75 (1.02)	2.42 (1.02)	5.41 (1.43)	5.33 (1.32)	3.10 (1.20)	4.96 (1.55)
Median [Min, Max]	5.43 [4.29, 13.9]	2.86 [0.143, 4.14]	5.43 [0.143, 13.9]	5.29 [0.429, 14.1]	3.29 [0.143, 5.29]	5.00 [0.143, 14.1]
Household size						
Mean (SD)	2.95 (1.35)	2.80 (1.58)	2.93 (1.38)	2.75 (1.31)	2.96 (1.34)	2.78 (1.32)
Median [Min, Max]	3.00 [1.00, 10.0]	2.00 [1.00, 9.00]	3.00 [1.00, 10.0]	3.00 [1.00, 11.0]	3.00 [1.00, 11.0]	3.00 [1.00, 11.0]
Age						
Mean (SD)	43.3 (11.2)	42.6 (17.8)	43.3 (12.1)	42.2 (10.5)	42.9 (11.3)	42.3 (10.6)
Median [Min, Max]	45.0 [16.0, 71.0]	46.0 [16.0, 78.0]	45.0 [16.0, 78.0]	42.0 [16.0, 69.0]	43.0 [18.0, 68.0]	42.0 [16.0, 69.0]
Gender						
Mean (SD)	1.52 (0.500)	1.74 (0.441)	1.54 (0.498)	1.45 (0.498)	1.83 (0.378)	1.52 (0.500)
Median [Min, Max]	2.00 [1.00, 2.00]	2.00 [1.00, 2.00]	2.00 [1.00, 2.00]	1.00 [1.00, 2.00]	2.00 [1.00, 2.00]	2.00 [1.00, 2.00]
Education						
Below Secondary	1509 (51.0%)	180 (53.9%)	1689 (51.3%)	1378 (15.1%)	442 (24.1%)	1820 (16.6%)
Completed Secondary	1448 (49.0%)	154 (46.1%)	1602 (48.7%)	4928 (53.9%)	998 (54.3%)	5926 (54.0%)
Above Sec	–	–	–	2840 (31.1%)	397 (21.6%)	3237 (29.5%)
Income						
Lowest quartile	371 (12.5%)	93 (27.8%)	464 (14.1%)	1311 (14.3%)	465 (25.3%)	1776 (16.2%)
Medium quartiles	1613 (54.5%)	157 (47.0%)	1770 (53.8%)	4092 (44.7%)	835 (45.5%)	4927 (44.9%)
Highest quartile	973 (32.9%)	84 (25.1%)	1057 (32.1%)	3743 (40.9%)	537 (29.2%)	4280 (39.0%)
Work day						
Mean (SD)	0.474 (0.499)	0.389 (0.488)	0.466 (0.499)	0.558 (0.497)	0.484 (0.500)	0.546 (0.498)
Median [Min, Max]	0 [0, 1.00]	0 [0, 1.00]	0 [0, 1.00]	1.00 [0, 1.00]	0 [0, 1.00]	1.00 [0, 1.00]

Note: * Main explanatory variable. Appendix 3.B contains histograms of work time by group.

3.3.4 Econometric analysis

We estimate three regression equations with the following specification:

$$Y_{i,j,d} = \beta_0 + \beta_1 WT_j + \beta_2 WT_j^2 + \beta_3 WT_j PT_j + \beta_4 PT_j + \beta_n C_{n,j,d} + \mu_d + u_{i,j} \tag{3.1}$$

In the first set of regressions (M1) Yi,j,d is the time person j spends on activity i (i = 1,..., 23) on day d (measured in minutes). The second set of models (M2) is estimated using the share of non-work time for each activity as an outcome ($Y_{i,j,d}$) to investigate relative changes in pastimes. In the third set (M3), energy use during leisure acts as the dependent variable, $Y_{i,j,d}$, so we can get an idea of potential environmental impacts. WT_j , represents the work time, i.e. the hours individual j spent in paid work on per day during the preceding week. PT_j indicates person j's employment status (1 for part-time employees). More time poverty implies less leisure time to reschedule certain activities to a different time slot. We further integrate interaction terms between WT and PT, as we expect the effect of an additional hour of work to be different depending on a respondent's employment status (reflecting the long-term level of work time). This reduces potential variation in work time across weeks, as the variable for weekly work hours is based on information about one week only. Additionally, being a part-time worker can capture other unobserved characteristics regarding a respondent's life stage or non-work duties, for instance, related to parenthood or education.

C_n, j, d is a vector of n person-specific control variables including age, gender, household size, education level, income group and a work day dummy (1 if respondent worked at least 30 min on the diary day). μ_d is a vector of time-specific fixed effects for month and day of the week, accounting for the idea that many social practices differ between days or month (Anderson, 2016; Torriti, 2017). u_i, j is the error term.[5]

As the correlation between employment status and work time (WT_j) is potentially high, we need to check for multicollinearity. The Pearson correlation coefficient for the two variables is -0.537 in France and -0.701 in Finland (both p-values $<$ 2.2e-16). As the generalised variance inflation factor (GVIF) for employment status and the interaction term are very high (41.24 and 18.15 for Finland; 16.07 and 11.80 for France), we add the covariates one by one, as recommended by Murray et al. (2012) for regression models with dummy variables. When we leave out the quadratic term (WT2), the GVIFs remain below the popular benchmark of 10 for both countries, indicating that there is no multicollinearity between the variables used.

[5]We also considered the sector of employment (public versus private), self-reported stress levels and work time of other household members. The employment sector and stress levels show a significant coefficient for few activities, but are only available for Finland. The work time of other household members proves to be significant only for certain activities among the French sample, while cutting the sample size approximately by half in both countries. We thus discarded these potential control variables. The results are available from the authors upon request.

3.4 Results

3.4.1 Time-use results

Absolute and relative time allocation

We first regress the absolute and relative duration of all 23 non-work activities on average daily working time. To show absolute and relative changes combined, Figure 3.2 represents the marginal effects of a change in WT for both countries in Cartesian coordinate system[6]. Each point represents one activity, its x-coordinate being the marginal relative change in the activity's share of leisure time associated with a one-hour increase of paid work per day, and its y-coordinate reflecting the marginal absolute change in minutes associated with an additional hour at work. Using this visualisation, we can separate how different types of activities relate to changes in times of paid work, both in absolute and relative terms. For example, the time spent on sleeping is lower among respondents with higher work hours (negative y-coordinate), while the share of leisure time spent on sleeping increases (positive x-coordinate). Activities in the upper right quadrant play a complementary role to work. For respondents with longer work hours, these activities increase in absolute and relative terms. For Finland none of the activities in this quadrant is significant. For the French sample, commuting and personal care show positive significant coefficients in both regression models, meaning that respondents with higher average work hours engage longer in these activities.

The lower left quadrant of Figure 3.2 includes all activities whose duration decreases in absolute and relative terms. There appears to be some sort of substitution between these activities and paid work. Examples are sports, reading or media use. All these activities are performed significantly less among people with longer work hours. In Finland child care 1 playing, talking, etc.) is also significantly lower among people who work more. In France many household tasks and chores, such as shopping, gardening, maintenance and food preparation also fall in this category.

The lower right quadrant shows what we call 'weak substitutes for work'. While these activities are reduced in absolute terms, they gain a larger share of leisure time when work hours increase. These are mostly activities which can only be reduced to some extent because they are essential for a healthy lifestyle, in particular sleep. Time is reallocated away from activities in the lower left quadrant towards those in the lower right quadrant for respondents with longer work hours. Expectedly no activities fall in the upper left quadrant (increase in absolute duration while falling as a share of leisure).

It is apparent that only a modest number of activities are affected significantly according to our pre-defined confidence levels. Religious activities, voluntary work and medical child care seem to be

[6]Note that we show the marginal effects for an average worker, i.e. calculating the effects using the mean of work time (WT) for each sample.

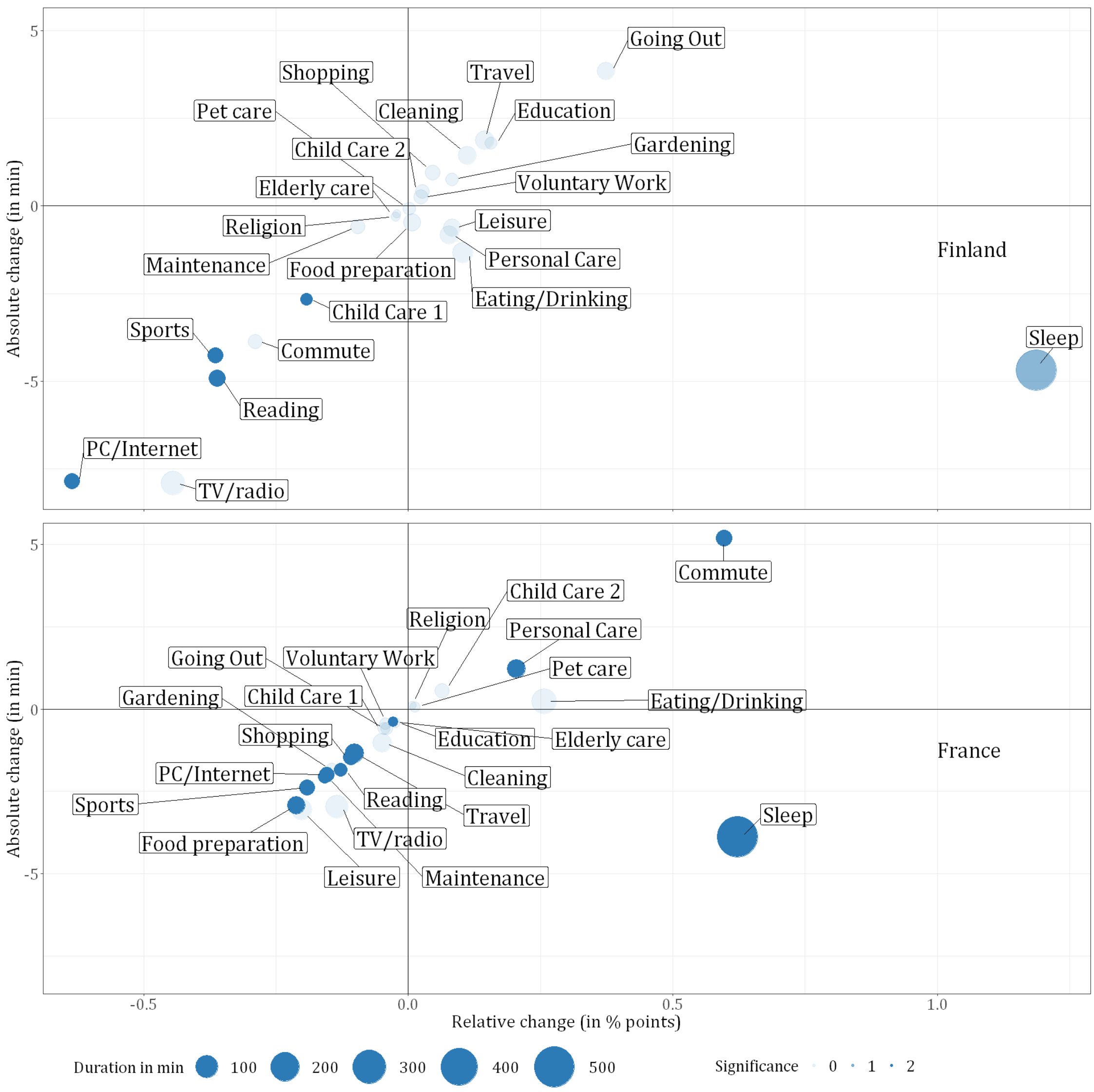


Figure 3.2: Relative and absolute changes in activity duration associated with a one-hour increase of work

Note: Finland (upper plot) and France (lower plot). Coordinates reflect the total marginal effect of a change in work time (including interaction term and squared term). Transparency of the points indicates whether the respective β_1 coefficients in the two models, M1 and M2, are at least statistically significant at the 5% level.

linked least to paid work, compared to other activities (small and mostly insignificant estimates). We find the largest relative effects for sleep in both countries. The French sample shows a higher number of significantly affected activities. This suggests a more diverse re-allocation of leisure when people face different work time. The detailed results in traditional table form can be found in Appendix 3.D.

Non-linear effects

Our second research question was how activity allocation changes, particularly whether changes in activity duration are linear, an implicit assumption in previous studies. Indeed, this does not seem to be the case for all activities. Several regression models show significant coefficients for the square of average daily work time (WT2), indicating relevant differences in the marginal effect of an hour worked on activity allocation. Figure 3.3 displays the predicted duration of activities where the change in time allotted is non-linearly related to work hours (with $p < 0.05$) for an average person. For activities with significant interaction between WT and the part-time dummy (PT), we plot the marginal effects for the average full-time employee and part-time employee, respectively.

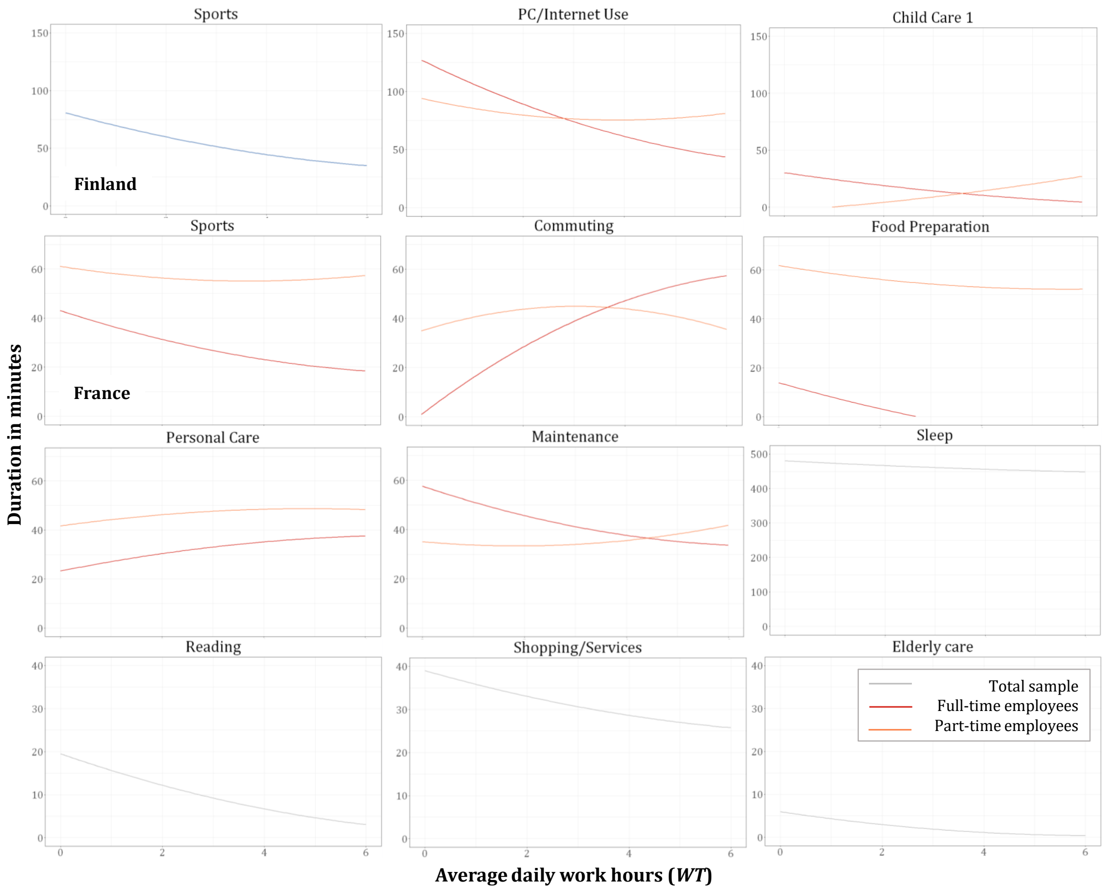


Figure 3.3: Significant non-linear regression lines

Note: Finland (upper row) and France (lower three rows). Coloured activities have a significantly different relationship for different employment groups.

In the Finnish sample three activities show significant ($p < 0.05$) quadratic terms: sports, PC/Internet use and child care 1. PC/Internet use and child care show significant group differences.[7] In line with the β_1 coefficients (M1), these activities all decrease with work hours, mostly in a convex manner, i.e. flattening with a rise in WT. An exception is child care among part-time employees, which is positively related with work time.

In the French sample nine activities show significant coefficients for the quadratic term: sports, commuting, food preparation, personal care, maintenance, sleep, reading, shopping and elderly care. Many of them also show significant group differences between the two employment types[8]. Commuting time and personal care increase with decreasing marginal effects. All other activities fall concavely when work time increases. Comparing the two employment groups, almost all activities change stronger among full-time workers than part-time workers, potentially indicating a more targeted adjustment by full-time workers, or put the other way around, more variation in the activity patterns of part-time workers. An exception is child care in Finland, where we see opposite effects between the two groups.

The insights are also interesting from an energy/environmental point of view. Energy-intensive commuting time increases in France, while the Finnish coefficient is negative (albeit not statistically significant). Furthermore, commuting in France increases more strongly with work time among full-time than part-time employees, for example. The reduction of maintenance time with rising work hours might point towards a 'throw-away' behaviour, rather than prolonging the lifetime of consumption goods.

3.4.2 Energy use results

In order to investigate the impact of different work and activity patterns on energy use (RQ iv), we calculated the total energy use per sample day according to the following formula:

$$EU_{total} = \sum_{d=1}^{D} \sum_{i=1}^{I} \sum_{h=1}^{H} A_{i,h,d} EI_{i,h} \tag{3.2}$$

$A_{i,h,d}$ is the duration of activity i (in hours) on day d of a household of type h. $EI_{i,h}$ is the corresponding energy intensity of each activity for the particular household type as calculated by Jalas and Juntunen (2015) and De Lauretis et al. (2017). They both provide average energy intensities per activity for six different household types distinct in terms of age, civil status and the number of children. It is not possible to compare energy use directly between the two countries for two reasons. First, they categorise activities differently. Secondly, they do not use the same

[7] The relationship between work hours and reading and education also differs significantly between employment groups. These are not displayed here because their squared term was non-significant (see Appendix 3.D).

[8] For France, PC/Internet use and education are also affected differently (with significant coefficients) for full-time and part-time workers (see Appendix 3.D).

indicator, namely direct energy use in France versus total energy use in Finland.

Our last set of regressions (M3) then estimates the relationship between average daily work time (WT) and individuals' energy use during leisure time. The time-use results from Section 3.4.1 serve as a guide for interpreting the changes in energy use we observe in this section. An overview of the contribution of the different activities to total energy use is provided in Appendix 3.F.

As energy use during leisure depends on the total leisure time available, we estimated both, total energy use (in kWh) and the energy-intensity of leisure (in kWh/h) as outcome variables. Table 3.2 presents the results of these regressions. Total energy use during leisure is significantly related to the time spent in paid work only in France. However, for Finland the estimate similarly points to an inverse relation, although it is not significant at our pre-defined level. As higher work time implies less leisure time by definition and thus less potential for energy use, the negative coefficients for total energy use are in line with what we expected. For France we find a significantly different effect of work time on energy use (or the slope of the curve) between the two employment groups.

Table 3.2: Effect of work time on total energy use and energy intensity of leisure

	Finland		**France**	
	Total energy use	Energy intensity	Total energy use	Energy intensity
WT	-8.255	-0.387	-1.701***	-0.021
	(5.824)	(0.277)	(0.242)	(0.011)
WT^2	0.325	0.016	0.089***	0.001
	(0.376)	(0.018)	(0.02)	(0.001)
Part-time	-14.709	-1.189	-1.376	0.015
	(21.359)	(1.017)	(0.827)	(0.037)
WT*Part-time	4.308	0.28	0.588**	0.005
	(5.292)	(0.252)	(0.210)	(0.009)
Age	-0.031	-0.007	0.103***	0.006***
	(0.086)	(0.004)	(0.008)	(0.0003)
Gender	4.833*	0.254*	4.620***	0.222***
	(2.103)	(0.100)	(0.163)	(0.007)
Completed 2ary	-4.031	-0.250*	-0.472*	-0.007
Education	(2.082)	(0.099)	(0.223)	(0.01)
Above 2ary			-1.037***	-0.036**
education			(0.267)	(0.012)
HH size	-14.861***	-0.743***	0.416***	0.018***
	(0.792)	(0.038)	(0.066)	(0.003)
Medium Income	10.942***	0.628***	-0.168	-0.01
	(3.117)	(0.148)	(0.245)	(0.011)
High Income	17.298***	0.941***	-0.267	-0.007
	(3.511)	(0.167)	(0.279)	(0.013)
WD	-35.185***	0.034	-12.506***	-0.161***
	(2.436)	(0.116)	(0.190)	(0.009)
Intercept	174.407***	7.995***	26.703***	0.877***
	(22.657)	(1.079)	(1.044)	(0.047)
Time FE	Yes	Yes	Yes	Yes
N	3,290	3,290	12,295	12,295
R^2	0.221	0.142	0.441	0.186
Adjusted R^2	0.214	0.135	0.439	0.184

Note: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

Regarding the energy intensity of non-work time, we cannot confirm that this variable changes with hours in paid work for Finland. None of the coefficients related to work time is significant. More important determinants for energy-intensity seem to be household size and gender. Age plays a significant role in France, whereas the coefficients for income groups are only significant for Finland. Note, however, that the energy reduction associated with less leisure is irrespective of the respondent's income group. Figure 3.4 illustrates the relationship between energy use and time in paid work for both countries.

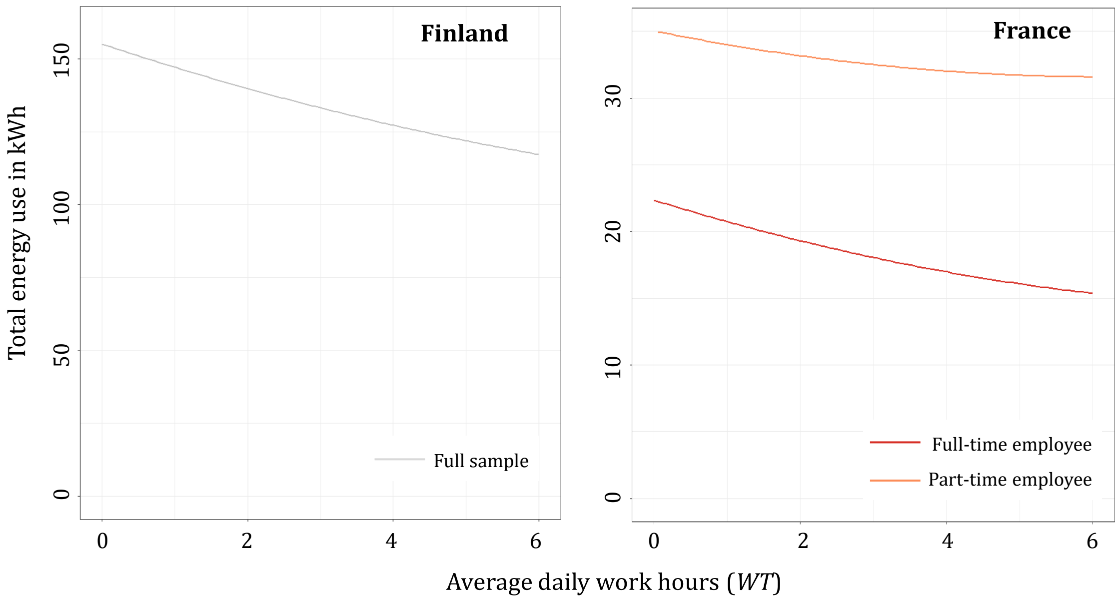


Figure 3.4: Regression line for energy use for different average daily work time

3.5 Discussion

We set out to investigate heterogeneity in work-leisure patterns and the resulting energy use. Our findings suggest that (1) certain activities have a non-linear relationship with working time, (2) marginal allocation of time differs between part-time and full-time workers, and (3) inter-country differences exist in the allocation of leisure[9]. These non-linear and group-specific patterns also translate into differentiated energy use in France, but not in Finland.

Our first research question aimed to identify the reallocation patterns of non-work time given different levels of paid work. We find that many, but not all activities are reduced when work hours increase. Among activities with the strongest reductions are sports, reading and PC/Internet use. Personal care and commuting seem to have a significant complementary role to work in France. Sleep falls in absolute duration, but increases in relation to other activities. As people work more,

[9]The inter-country difference in the effect of work time on activity duration (M1) is statistically significant ($p<0.05$) for commuting, food preparation, personal care, reading, cleaning, PC use, going out, maintenance, education and child care. Results are available from the authors on request.

time is shifted away from care, sports, reading and PC/Internet use towards sleep in both countries. While we observe some similarities, there are also important differences in the reallocation of time between Finland and France.

Most notably, the correlation between commuting and work time is positive in France, but negative in Finland. There may be several explanations for this. For instance that telecommuting may be more common in Finland – the country has a very high share of 'e-nomads' (Eurofound, 2012), or that the distance to the workplace is shorter. Differences in transportation modes or traffic can play a role as well. The bottom line is that it is important to understand these context-specific effects when one aims to implement policies related to work and energy use. The higher number of significantly affected activities in France indicates a more diverse re-allocation of time. This may be due to a more heterogeneous structure of the population (for example due to migration backgrounds), or due to distinct work culture and institutions. Household chores, such as shopping, cleaning or food preparation showed positive coefficients for Finland and negative ones for France. This is in line with the common dual-earner classification for Finland, versus a home-maker-breadwinner distinction between household members in France. While we did not study such cultural implications and explanations here, it is important to acknowledge that these differences between countries exist.

Regarding research question (ii) our results suggest that not all activities are simply scaled down linearly when work hours increase. Reductions in some activities are stronger for the first hours of work and flattening for longer work hours and vice versa (see Figure 3.3). Due to these distinct marginal reductions, the composition of leisure time in relative terms changes under distinct amounts of work hours. Typically, time is deducted from certain leisure activities and household chores, in favour of activities sustaining a person physically (e.g. sleep or personal care). The time for voluntary work and religious activities is hardly affected in both countries. Among activities with a significant quadratic term, changes are typically stronger at first and flattening for longer hours. This indicates that there is a strong effect of work time on particular activities, which diffuses to a wider range of activity changes among respondents who work a lot.

Research question (iii) concerned the moderation of effects by a respondent's employment status. We find that allocation of non-work time differs between part-time and full-time employees, especially in France. This is a potential reflection of stricter separation of tasks within households. The direction of change for most activities is similar when considering the average person (see Figure 3.2), and changes seem to be stronger for the full-time employees. One could interpret this as a more consistent re-allocation of time within this group, whereas time is reallocated to more activities among part-time employees. One very interesting result is the positive effect of work time on child care for part-time employees in Finland. One possible explanation is related to life stages. In the group of part-time employees with shorter work hours (<15) the share of students is more than twice as high as among part-time workers with 15 or more hours per week. The former also have 13% less children on average. Generally, we see that the allocation of leisure time is more diverse in France than in Finland. This is possibly due to cultural diversity compared to a more homogeneous population in Finland.

Regarding our last research question, total energy use during leisure falls with rising hours at work for France. This makes sense, because it reflects an overall reduction in time during which we account for energy use. Interestingly, we cannot confirm this result for Finland. One reason could be a shift towards more energy-intensive leisure activities among respondents who work more. However, we do not see changes in the energy-intensity of leisure either. Hence, another explanation is more likely. Embodied energy, which is measured for Finland, includes energy use throughout the production process of goods and can be expected to vary less with time spent using these goods, whereas direct energy use used for France is typically directly linked to the use of goods or services (e.g. transport fuels for driving your car). Comparing this with the significant impact of income group affiliation in Finland, a tentative conclusion may be that while work hours are a more relevant for direct energy use, income effects dominate overall energy use (including embodied energy). The non-linear relationship with different slopes for part-time and full-time workers in the French sample reflects the results of the time-reallocation (Figure 3.3). As mentioned before, there is no significant effect of work time on the energy intensity of leisure in either of the countries. We can conclude that there is no time-effect on energy intensity.

Similar to the findings in Buhl and Acosta (2016), we see relatively large time-use effects for certain hobbies, in particular sports and reading. On the other hand, we see less significant changes in household work and the largest effects for sleep. The latter findings are conflicting with previous evidence (Buhl and Acosta, *ibid.*). One reason could be that – contrary to Buhl and Acosta (2016) – we are not using sample day work as an independent variable, but weekly work hours. Thus, the coefficients from our study can be clearly interpreted as the extent to which time spent on an activity differs for people who engage on average one more hour per day in paid work and do not include intra-personal variation between sample days. Our energy use results are comparable to results of Nässén and Larsson (2015). We find that for a typical full time employee, a work time reduction by 1% corresponds to an increase in energy use by approximately 0.22% in Finland and 0.25% in France (0.05% for part-time employees), compared to 0.23% in Nässén and Larsson (*ibid.*)'s study for Sweden.[10]

Contrary to Gough et al. (2011), who find that the effect of hours worked on GHG emissions in the UK is statistically insignificant when combined with employment status, we see that for France

[10] Note that our estimates are not a pure time effect, as we cannot perfectly control for all income effects.

the WT coefficient remains significant. For the same country, the effect of an additional work hour on total energy use differs significantly between the two groups, with reductions in energy use associated with an extra hour of work being significantly weaker for part-time employees compared to full-time employees ($p < 0.01$).

3.5.1 Limitations

This study faces several limitations that we would like to mention. First, we had to rely on cross-sectional data from 2009 for our analysis. Due to the nature of the data we abstain from any causal inference or policy scenarios. Scientists and policy makers could greatly benefit from more frequent data collection in a time series manner to understand dynamics of different lifestyles and how they drive energy use.

Second, we relied on other studies for the energy use estimates, which were not overlapping entirely. This complicates the inter-country comparison regarding energy use, although it should not affect our main results. As recently highlighted also by Antal et al. (2020) it is generally a challenging task to match activity data with material footprints, as expenditure surveys and time diaries are collected separately. Collecting these data together could improve estimations of energy (or material) intensity of different activities greatly. One problem is, for instance, that the energy intensities for a given household type are fixed and cannot change over time.

Third, household income has been discussed widely as one of the main drivers for energy use or GHG emissions more generally (Gough et al., 2011; Büchs and Schnepf, 2013; Druckman and Jackson, 2016). While we control for income quantiles in all regression models and our household typology reflects income to a certain extent, a lack of detailed income data prevents us from clearly separating time and income effects. We cannot control for any effects of income adjustments following an actual work time reduction on energy use or differences within a household's income group. Additionally, better income data would be desirable to discuss the role of income in time budgeting, given differences in employment status.

3.6 Conclusions

Few studies have undertaken time-use analyses in the context of labour markets, leisure activities and energy use. Here we performed a time-use analysis of the relationship between work time, leisure and energy use of individuals in Finland and France. Using time-diary data on 23 activities, we applied an econometric approach to study how time is allocated among individuals with distinct levels of work time and different employment status. Using energy intensity factors per time unit of each activity for six different household types, we calculated total energy use during leisure as well as energy intensity (per hour of leisure). From this we estimated the relationship between work hours and energy use.

We find heterogeneity in this work-energy relationship, especially within the French sample, where total energy use is affected differently between part-time and full-time workers. In France, energy use reductions are stronger among full-time than part-time employees. We also find a non-linear change in total energy use for respondents with distinct levels of work time. Energy use reductions are stronger during the first hours of work, but flattening for longer hours. The differences in patterns between the two countries may be due to the measure of energy use applied. In particular, direct energy use, as measured for France, is likely to vary much more with activity time than indirect energy use (occurring during production) as captured by the Finnish energy data. To study this further, internationally comparable energy use estimates of activities are needed. However, one should generally avoid simply transferring results for one country to another.

The changes in absolute duration of activities that go along with varying work hours, as well as shifts in respective relative shares of leisure activities were only somewhat similar for both countries. Higher working hours lead to time being shifted away from exercising, reading and PC use to self-sustaining activities, such as personal care or sleeping, and in the case of France to commuting. Variation in these activities across employment groups in France leads to the distinct marginal effects on energy intensity between the two worker types.

More research is needed to clarify the variation between employment groups. This could help overcome the gap in micro- and macro-estimates of the work-time-energy relationship other studies have found. The variation in marginal effects of work hours on energy use also implies that changing work hours among distinct employment groups can lead to different environmental outcomes. Hence, paying close attention to time-use patterns of different segments of the labour force is crucial for policy makers when combing the aims of 'decent work' and climate action', as formulated in the United Nations' Sustainable Development Goals (Desa et al., 2016). Relatedly, carbon taxation is frequently linked to cuts in labour-related taxes, such as in Canada (Beck et al., 2015) or Finland (Sumner et al., 2011), which may affect energy use and emissions through work time and activity patterns. In view of this, taking time-use into account could help to formulate better targeted and thus more effective climate policies.

References

Anderson, B. (2016). Laundry, energy and time: Insights from 20 years of time-use diary data in the United Kingdom. *Energy Research & Social Science*, 22:125–136.

Antal, M., Plank, B., Mokos, J., and Wiedenhofer, D. (2020). Is working less really good for the environment? A systematic review of the empirical evidence for resource use, greenhouse gas emissions and the ecological footprint. *Environmental Research Letters*, 16(1):013002.

Bank, W. (2015). Total primary energy use per person. data retrieved from World Development Indicators, February 1, 2021, `http://data.worldbank.org/indicator/SP.DYN.LE00.FE.IN`.

Beck, M., Rivers, N., Wigle, R., and Yonezawa, H. (2015). Carbon tax and revenue recycling: Impacts on households in British columbia. *Resource and Energy Economics*, 41:40–69.

Bovenberg, A. (1999). Green tax reforms and the double dividend: an updated reader's guide. *International tax and public finance*, 6(3):421–443.

Büchs, M. and Schnepf, S. V. (2013). Who emits most? associations between socio-economic factors and uk households' home energy, transport, indirect and total CO_2 emissions. *Ecological Economics*, 90:114–123.

Buhl, J. and Acosta, J. (2016). Work less, do less? *Sustainability Science*, 11(2):261–276.

De Lauretis, S., Ghersi, F., and Cayla, J.-M. (2017). Energy consumption and activity patterns: an analysis extended to total time and energy use for French households. *Applied Energy*, 206:634–648.

Desa, U. N. (2016). Transforming our world: The 2030 agenda for sustainable development. *United Nations.* URL: https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable %20Development%20web.pdf.

Druckman, A., Buck, I., Hayward, B., and Jackson, T. (2012). Time, gender and carbon: a study of the carbon implications of british adults' use of time. *Ecological Economics*, 84:153–163.

Druckman, A. and Jackson, T. (2016). Understanding households as drivers of carbon emissions. In *Taking stock of industrial ecology*, pages 181–203. Springer, Cham.

Eurofound (2012). Fifth European working conditions survey.

Gershuny, J. (2013). Multinational time use study.

Gough, I., Abdallah, S., Johnson, V., Ryan-Collins, J., and Smith, C. (2011). The distribution of total greenhouse gas emissions by households in the UK, and some implications for social policy. *LSE STICERD Research Paper No. CASE152*.

Jackson, T. and Victor, P. (2011). Productivity and work in the 'green economy': Some theoretical reflections and empirical tests. *Environmental Innovation and Societal Transitions*, 1(1):101–108.

Jalas, M. (2002). A time use perspective on the materials intensity of consumption. *Ecological Economics*, 41(1):109–123.

Jalas, M. (2005). The everyday life context of increasing energy demands: Time use survey data in a decomposition analysis. *Journal of Industrial Ecology*, 9(1-2):129–145.

Jalas, M. and Juntunen, J. K. (2015). Energy intensive lifestyles: Time use, the activity patterns of consumers, and related energy demands in Finland. *Ecological Economics*, 113:51–59.

King, L. C. and van den Bergh, J. C. (2017). Worktime reduction as a solution to climate change: five scenarios compared for the UK. *Ecological Economics*, 132:124–134.

Knight, K. W., Rosa, E. A., and Schor, J. B. (2013). Could working less reduce pressures on the environment? A cross-national panel analysis of OECD countries, 1970–2007. *Global Environmental Change*, 23(4):691–700.

Minx, J. C. and Baiocchi, G. (2009). Time use and sustainability: An input-output approach in mixed units. In *Handbook of input-output economics in industrial ecology*, pages 819–846. Springer.

Murray, L., Nguyen, H., Lee, Y.-F., Remmenga, M. D., and Smith, D. W. (2012). Variance inflation factors in regression models with dummy variables. *Conference on Applied Statistics in Agriculture*. https://doi.org/10.4148/2475-7772.1034.

Nässén, J. and Larsson, J. (2015). Would shorter working time reduce greenhouse gas emissions? an analysis of time use and consumption in Swedish households. *Environment and Planning C: Government and Policy*, 33(4):726–745.

Parent-Thirion, A., Fernández-Macías, E., Hurley, J., and Vermeylen, G. (2007). Fourth European working conditions survey.

Rosnick, D. and Weisbrot, M. (2007). Are shorter work hours good for the environment? A comparison of US and European energy consumption. *International Journal of Health Services*, 37(3):405–417.

Schipper, L., Bartlett, S., Havk, D., and Vine, E. (1989). Linking Life-Styles and Energy Use: A matter of Time. *Annual Review of Energy and the Environment*, 4:273–320.

Schor, J. B. (2005). Sustainable consumption and worktime reduction. *Journal of industrial ecology*, 9(1-2):37–50.

Smetschka, B., Wiedenhofer, D., Egger, C., Haselsteiner, E., Moran, D., and Gaube, V. (2019). Time matters: the carbon footprint of everyday activities in Austria. *Ecological Economics*, 164:106357.

Sumner, J., Bird, L., and Dobos, H. (2011). Carbon taxes: a review of experience and policy design considerations. *Climate Policy*, 11(2):922–943.

Torriti, J. (2017). Understanding the timing of energy demand through time use data: Time of the day dependence of social practices. *Energy research & social science*, 25:37–47.

Wiedenhofer, D., Smetschka, B., Akenji, L., Jalas, M., and Haberl, H. (2018). Household time use, carbon footprints, and urban form: a review of the potential contributions of everyday living to the 1.5 C climate target. *Current opinion in environmental sustainability*, 30:7–17.

Yu, B., Zhang, J., and Wei, Y.-M. (2019). Time use and carbon dioxide emissions accounting: An empirical analysis from china. *Journal of Cleaner Production*, 215:582–599.

Appendix 3.A Activities & categorisations by other authors

TUS activities	Description of activities according to MTUS	Jalas & Juntunen (2015)	De Lauretis et al. (2017)
Sleep	Sleep and naps	-	Sleep
Eating & Drinking	Meals or snacks, also at work, school or elsewhere	Eating	Eating at home
Personal care	Wash, dress, care for yourself	Personal hygiene, dressing	Personal time
Education	Regular schooling, homework, other education	Studies	Work & study
Food preparation	Food preparation, cooking, setting table, washing dishes	Eating	Housework: meals
Cleaning, etc.	Cleaning, laundry, ironing, repair clothing, other domestic work	Housework	Housework: home, Housework: clothes
Maintenance	Home/vehicle maintenance or improvement, collecting fuel	Maintenance work	Housework: home
Shopping & Services	Purchasing goods, consuming personal care services/other services	Shopping, personal services, public administration and related trips	Shopping & administration
Gardening	Gardening, foraging, hunting, fishing	Maintenance work	Housework: home
Pet care	Walking dog, etc.	-	Care
Adult care	Caring for adult person, e.g. elderly	-	Care
Medical child care (Child care 2)	Physical or medical child care, supervision	-	Care
Child care (Child care 1)	Teach skills, help with homework, read, talk play with children	-	Care
Religion	Worship and religious activity	-	-
Voluntary work	Voluntary work, civic or organisational activity	-	-
Commuting	Travel to/from work, education related travel	Trips to work and study	Commuting (ancillary)
Travelling	Travel for voluntary/ civic/ religious activity, care-related travel, travel for shopping, etc.	Free time trips	Other travel time (ancillary)
Sports exercise	General sports or exercise, walking, cycling	Sports and recreation	Non energy-intensive leisure Sports & outings
TV & radio	Listen to music, radio, watching TV/DVD or streaming content	Television	Energy-intensive leisure
Reading	Reading	Reading	Non energy-intensive leisure
PC/Internet use	Play computer games, email, surfing the Internet, programming, computing	Phone conversations	Energy-intensive leisure
Going out	Out-of-home leisure, attending sports or public event, cinema, theatre, opera, concert, restaurant, café, bar, pub, party, reception, social event, gambling and other	Eating Cultural events Hobbies	Eating out Sports & outings
Leisure	Receive or visit friends, conversation, games, general indoor leisure, artistic or musical activity, written correspondence, knit, craft or hobbies, relaxing, thinking	Phone conversations Hobbies	Non energy-intensive leisure
Paid work	All types of jobs, looking for work	-	Work & study

Appendix 3.B Average work time distribution

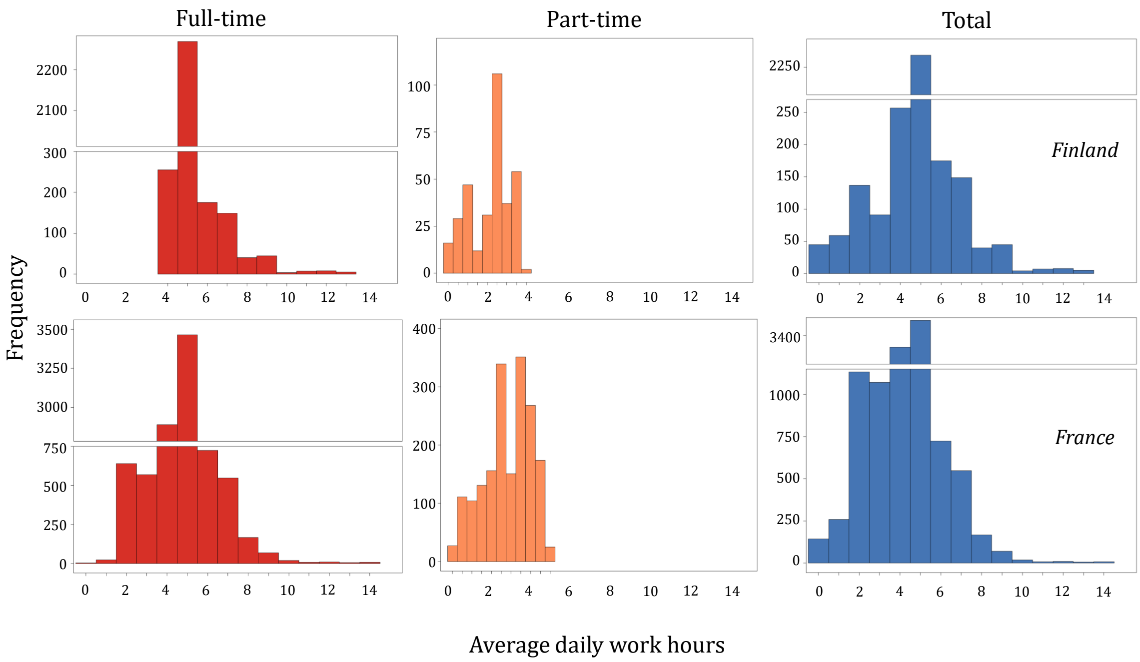


Figure 3.5: Histogram of the average work time per day (WT)

Note: Please note the axis breaks. Values plotted here are not weighted.

Appendix 3.C Statistical tests

Table 3.3: Results of the Kolmogorov-Smirnov (K-S) and Wilcoxon rank sum tests

	Variable	N	Mean of missing observations	Mean of all data	p-value (K-S test)	p-value (Wilcoxon test)
Finland	Household size	312	3.154	2.954	0.323	0.009
	Age	312	45.051	43.419	0.109	0.042
	Gender	312	1.513	1.541	0.977	0.339
	Education	312	1.670	1.646	0.647	0.083
	Income group	312	2.196	2.182	0.937	0.621
	Employment status	312	1.144	1.105	0.774	0.033
France	Household size	1485	2.908	2.797	0.137	0.004
	Age	1485	42.993	42.363	0.003	0.090
	Gender	1485	1.576	1.524	0.001	0.000
	Education	1485	41.642	40.004	0.000	0.000
	Income group	1485	2.313	2.238	0.004	0.000
	Employment status	1485	1.343	1.188	0.000	0.000

Note:A p-value > 0.1 for the K-S test means that one cannot reject the hypothesis that the two samples come from the same distribution. For the Wilcox rank sum test (equivalent to Mann-Whitney test) a p-value < 0.1 means that one cannot reject the hypothesis that one of the distributions generally has larger values. N: number of missing observations tested.

Appendix 3.D Detailed regression results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
WT	9.381***	−7.785***	−4.109***	−0.210	−2.172***	−9.290***	−4.937***	−2.228***	−6.574***	−2.625***	−2.636***	−6.063***	−2.561***	−1.404**	−0.066	−3.007***	−2.863***	−0.242	−2.227**	−4.307***	0.318*	−3.338***	−1.108***
	(0.384)	(0.935)	(0.530)	(0.430)	(0.524)	(1.232)	(0.844)	(0.610)	(0.727)	(0.735)	(0.644)	(0.986)	(0.508)	(0.481)	(0.414)	(0.715)	(0.629)	(0.136)	(0.698)	(1.217)	(0.146)	(0.612)	(0.301)
WT^2	−0.533***	0.142	0.098*	−0.054	0.019	−0.216*	0.135	−0.023	0.198**	0.018	0.010	0.197*	−0.022	0.036	−0.040	0.013	0.146**	0.010	0.050	−0.263*	−0.028*	0.088	0.021
	(0.034)	(0.082)	(0.047)	(0.038)	(0.046)	(0.109)	(0.074)	(0.054)	(0.064)	(0.065)	(0.057)	(0.087)	(0.045)	(0.042)	(0.037)	(0.063)	(0.055)	(0.012)	(0.062)	(0.107)	(0.013)	(0.054)	(0.027)
Part-time	5.386*	−8.518	−9.786**	3.380	2.309	−16.257*	9.227	1.483	−11.540**	9.540*	−0.759	1.430	0.514	0.171	−1.618	−7.078	50.493***	0.227	−2.387	−2.104	0.374	−17.606***	−6.881***
	(2.161)	(5.262)	(2.982)	(2.421)	(2.950)	(6.932)	(4.747)	(3.432)	(4.092)	(4.136)	(3.622)	(5.547)	(2.856)	(2.707)	(2.330)	(4.021)	(3.538)	(0.766)	(3.925)	(6.848)	(0.820)	(3.444)	(1.692)
Unempl	−1.653	−20.774***	6.574*	1.579	−1.729	−7.524	17.298***	4.826	−8.796*	25.761***	−7.058	−19.937***	−7.763**	2.737	7.990***	−1.093	−1.462	−1.718*	−4.171	32.840***	−0.387	−11.037**	−5.467**
	(2.177)	(5.301)	(3.004)	(2.439)	(2.972)	(6.983)	(4.782)	(3.458)	(4.122)	(4.166)	(3.649)	(5.588)	(2.877)	(2.727)	(2.348)	(4.051)	(3.564)	(0.771)	(3.954)	(6.899)	(0.826)	(3.470)	(1.704)
Age	−0.265***	−0.067	0.698***	0.005	0.455***	−0.992***	0.064	0.950***	0.744***	−1.259***	0.104	−0.485***	0.168**	0.298***	−0.092*	0.313***	−0.729***	0.020	0.171*	0.528***	0.025	−0.467***	−0.200***
	(0.042)	(0.102)	(0.058)	(0.047)	(0.057)	(0.134)	(0.092)	(0.067)	(0.079)	(0.080)	(0.070)	(0.108)	(0.055)	(0.053)	(0.045)	(0.078)	(0.069)	(0.015)	(0.076)	(0.133)	(0.016)	(0.067)	(0.033)
Gender	2.257*	−5.081*	26.654***	11.804***	−2.149	−2.022	10.127***	2.876	27.558***	−18.307***	−1.249	−6.411*	4.451**	−0.291	4.177***	−24.158***	3.788*	−0.237	−1.801	−37.449***	0.682	4.237**	0.901
	(1.028)	(2.503)	(1.418)	(1.152)	(1.403)	(3.297)	(2.258)	(1.632)	(1.946)	(1.967)	(1.723)	(2.638)	(1.358)	(1.288)	(1.108)	(1.912)	(1.683)	(0.364)	(1.867)	(3.257)	(0.390)	(1.638)	(0.805)
Completed 2ary Education	−0.970	0.125	−1.693	−0.407	3.141*	−3.312	2.574	11.685***	−0.296	5.045*	2.586	−3.708	0.471	−1.170	−1.932	−2.715	−3.122	0.234	−2.680	−13.669***	−0.477	7.251***	3.245***
	(1.050)	(2.558)	(1.450)	(1.177)	(1.434)	(3.370)	(2.308)	(1.669)	(1.989)	(2.011)	(1.761)	(2.697)	(1.388)	(1.316)	(1.133)	(1.955)	(1.720)	(0.372)	(1.908)	(3.329)	(0.399)	(1.674)	(0.822)
HH size	−0.999*	−1.707	3.087***	−1.737***	1.738**	−1.567	0.065	−1.093	4.499***	−2.588***	−2.844***	−4.149***	0.349	0.655	−1.187**	1.256	0.681	0.078	−0.510	−6.819***	0.089	9.125***	3.546***
	(0.399)	(0.973)	(0.551)	(0.448)	(0.545)	(1.281)	(0.877)	(0.634)	(0.756)	(0.765)	(0.670)	(1.025)	(0.528)	(0.500)	(0.431)	(0.743)	(0.654)	(0.142)	(0.726)	(1.266)	(0.152)	(0.637)	(0.313)
Medium Income	4.101**	1.648	−2.033	0.459	0.188	−8.938	2.481	−6.448**	3.727	−1.163	2.090	−5.194	−1.870	−0.680	3.728*	7.899**	−1.531	0.143	−2.409	−0.036	0.883	3.215	0.420
	(1.503)	(3.661)	(2.074)	(1.684)	(2.052)	(4.822)	(3.302)	(2.388)	(2.847)	(2.877)	(2.520)	(3.859)	(1.987)	(1.883)	(1.621)	(2.797)	(2.461)	(0.533)	(2.730)	(4.764)	(0.571)	(2.396)	(1.177)
High Income	5.999***	3.359	−3.169	3.036	4.164	−18.530***	0.476	−5.848*	7.929*	2.229	8.231**	1.114	−4.639*	−1.625	3.058	1.080	0.191	0.578	−1.133	1.621	0.138	−5.745*	−2.134
	(1.716)	(4.178)	(2.368)	(1.923)	(2.343)	(5.504)	(3.769)	(2.725)	(3.249)	(3.284)	(2.876)	(4.405)	(2.268)	(2.150)	(1.850)	(3.193)	(2.809)	(0.608)	(3.117)	(5.438)	(0.651)	(2.735)	(1.343)
Sometimes rushed	2.348	6.413	0.992	1.571	−1.989	−1.311	−1.814	−6.604**	3.454	−13.713***	−0.244	3.186	2.409	1.401	1.058	−0.454	2.089	−1.479**	5.956*	−9.137	−0.529	5.926*	1.686
	(1.582)	(3.853)	(2.183)	(1.773)	(2.160)	(5.075)	(3.475)	(2.513)	(2.996)	(3.028)	(2.652)	(4.061)	(2.091)	(1.982)	(1.706)	(2.944)	(2.590)	(0.560)	(2.874)	(5.014)	(0.601)	(2.522)	(1.238)
Always rushed	1.974	8.213	1.097	5.112*	−0.365	−5.319	−6.972	−9.007**	7.049*	−17.789***	0.199	5.922	8.424***	−0.029	2.944	1.898	3.514	−1.587*	6.536	−18.740**	0.142	6.657*	1.121
	(1.858)	(4.525)	(2.564)	(2.082)	(2.537)	(5.961)	(4.082)	(2.952)	(3.519)	(3.557)	(3.115)	(4.770)	(2.456)	(2.328)	(2.004)	(3.458)	(3.042)	(0.658)	(3.375)	(5.889)	(0.706)	(2.962)	(1.455)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	(2.444)	(5.953)	(3.373)	(2.739)	(3.337)	(7.841)	(5.369)	(3.882)	(4.629)	(4.678)	(4.098)	(6.275)	(3.231)	(3.062)	(2.636)	(4.548)	(4.002)	(0.866)	(4.440)	(7.746)	(0.928)	(3.896)	(1.913)
WT*Part-time	−0.509	1.100	0.505	−0.741	0.123	1.269	−0.601	0.547	0.998	0.022	0.284	−0.127	−0.399	−0.202	−0.075	1.286	−5.359***	−0.074	−0.431	−0.740	−0.100	2.252**	1.026**
	(0.442)	(1.077)	(0.610)	(0.496)	(0.604)	(1.419)	(0.971)	(0.702)	(0.837)	(0.846)	(0.741)	(1.135)	(0.585)	(0.554)	(0.477)	(0.823)	(0.724)	(0.157)	(0.803)	(1.401)	(0.168)	(0.705)	(0.346)
WT*Unempl	0.399	1.575	−2.269	0.493	−0.379	6.507	−0.830	−2.957	−2.264	1.291	0.213	−1.237	−1.613	−1.271	−2.694	0.089	3.551	0.409	2.439	−2.722	−0.003	0.928	0.681
	(1.623)	(3.953)	(2.240)	(1.819)	(2.216)	(5.207)	(3.566)	(2.578)	(3.074)	(3.107)	(2.721)	(4.167)	(2.146)	(2.034)	(1.750)	(3.020)	(2.658)	(0.575)	(2.948)	(5.144)	(0.616)	(2.587)	(1.271)
Intercept	5.914	73.230***	−21.122***	27.744***	55.231***	667.087***	36.151***	13.591*	−40.141***	144.750***	38.204***	89.352***	−2.966	−5.473	10.336*	44.362***	32.723***	3.705**	12.762	233.822***	−2.092	7.830	12.829***
	(3.788)	(9.227)	(5.229)	(4.245)	(5.173)	(12.154)	(8.323)	(6.018)	(7.175)	(7.252)	(6.352)	(9.726)	(5.008)	(4.747)	(4.086)	(7.050)	(6.203)	(1.342)	(6.882)	(12.007)	(1.438)	(6.039)	(2.966)
N	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654
R^2	0.335	0.118	0.227	0.081	0.080	0.279	0.097	0.118	0.181	0.159	0.057	0.098	0.092	0.072	0.036	0.094	0.136	0.018	0.024	0.186	0.014	0.134	0.100
Adjusted R^2	0.329	0.110	0.220	0.073	0.072	0.273	0.089	0.111	0.174	0.152	0.049	0.091	0.084	0.064	0.027	0.086	0.129	0.010	0.016	0.179	0.006	0.127	0.092

Note: * $p<0.05$; ** $p<0.01$; *** $p<0.001$

Activity code: Commute (1), Travel (2) Food preparation (3) Personal care (4), Eating/Drinking (5), Sleep (6), Leisure (7), Reading (8), Cleaning (9), Computer/PC (10), Sport (11), Going out (12), Shopping/Services (13), Gardening (14), Pet care (15), Maintenance (16), Education (17), Religion (18), Voluntary work (19), TV/Radio (20), Elderly care (21), Child care 1(22), Child care 2(23).

Figure 3.6: *Finland, Model 1: Absolute duration per activity in minutes*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
WT	0.735***	−0.338***	−0.093*	0.124***	−0.005	0.789***	−0.175**	0.005	−0.283***	−0.080	−0.060	−0.302***	−0.043	−0.061	0.062	−0.119*	−0.180***	−0.015	−0.068	0.281**	0.037**	−0.155***	−0.056*
	(0.039)	(0.071)	(0.041)	(0.036)	(0.045)	(0.106)	(0.067)	(0.048)	(0.057)	(0.057)	(0.052)	(0.077)	(0.041)	(0.036)	(0.034)	(0.055)	(0.047)	(0.010)	(0.055)	(0.100)	(0.013)	(0.046)	(0.023)
WT^2	−0.025***	−0.002	−0.003	0.003	0.019***	0.058***	0.004	−0.008	0.006	−0.002	−0.007	0.010	−0.009**	0.0003	−0.006	−0.004	0.009*	0.001	−0.001	−0.041***	−0.003*	0.001	0.001
	(0.003)	(0.006)	(0.004)	(0.003)	(0.004)	(0.009)	(0.006)	(0.004)	(0.005)	(0.005)	(0.005)	(0.007)	(0.004)	(0.003)	(0.003)	(0.005)	(0.004)	(0.001)	(0.005)	(0.009)	(0.001)	(0.004)	(0.002)
Part-time	0.320	−0.606	−0.723**	0.251	0.134	−0.882	0.633	0.120	−0.886**	0.633*	−0.091	0.125	−0.005	0.004	−0.118	−0.568	3.550***	0.017	−0.145	−0.018	0.032	−1.277***	−0.500***
	(0.220)	(0.400)	(0.232)	(0.205)	(0.254)	(0.595)	(0.378)	(0.271)	(0.322)	(0.322)	(0.291)	(0.435)	(0.232)	(0.202)	(0.193)	(0.311)	(0.262)	(0.054)	(0.308)	(0.562)	(0.075)	(0.258)	(0.130)
Unempl	−0.130	−1.447***	0.480*	0.137	−0.143	−0.487	1.239**	0.326	−0.579	1.726***	−0.468	−1.363**	−0.575*	0.208	0.558**	−0.092	−0.094	−0.121*	−0.247	2.197***	−0.022	−0.733**	−0.372**
	(0.222)	(0.403)	(0.234)	(0.207)	(0.256)	(0.599)	(0.381)	(0.273)	(0.324)	(0.325)	(0.293)	(0.438)	(0.233)	(0.204)	(0.194)	(0.314)	(0.264)	(0.055)	(0.310)	(0.566)	(0.076)	(0.260)	(0.131)
Age	−0.024***	−0.006	0.055***	0.002	0.038***	−0.084***	0.006	0.077***	0.058***	−0.100***	0.007	−0.037***	0.013**	0.022***	−0.008*	0.023***	−0.053***	0.001	0.014*	0.046***	0.002	−0.036***	−0.016***
	(0.004)	(0.008)	(0.005)	(0.004)	(0.005)	(0.012)	(0.007)	(0.005)	(0.006)	(0.006)	(0.006)	(0.008)	(0.004)	(0.004)	(0.004)	(0.006)	(0.005)	(0.001)	(0.006)	(0.011)	(0.001)	(0.005)	(0.003)
Gender	0.217*	−0.407*	2.147***	1.040***	−0.245*	−0.300	0.787***	0.249	2.264***	−1.477***	−0.111	−0.473*	0.402***	−0.022	0.352***	−1.911***	0.319*	−0.017	−0.122	−3.070***	0.055	0.270*	0.051
	(0.105)	(0.190)	(0.110)	(0.098)	(0.121)	(0.283)	(0.180)	(0.129)	(0.153)	(0.153)	(0.138)	(0.207)	(0.110)	(0.096)	(0.092)	(0.148)	(0.125)	(0.026)	(0.147)	(0.267)	(0.036)	(0.123)	(0.062)
Completed 2ary Education	−0.096	0.023	−0.133	0.038	0.180	−0.148	0.174	0.931***	−0.030	0.366*	0.227	−0.229	−0.002	−0.122	−0.173	−0.253	−0.204	0.018	−0.191	−1.147***	−0.041	0.560***	0.249***
	(0.107)	(0.195)	(0.113)	(0.100)	(0.124)	(0.289)	(0.184)	(0.132)	(0.156)	(0.157)	(0.141)	(0.211)	(0.113)	(0.098)	(0.094)	(0.151)	(0.128)	(0.026)	(0.150)	(0.273)	(0.037)	(0.126)	(0.063)
HH size	−0.120**	−0.105	0.266***	−0.145***	0.162***	−0.147	0.048	−0.108*	0.370***	−0.224***	−0.245***	−0.328***	0.044	0.052	−0.097**	0.089	0.043	0.006	−0.019	−0.578***	0.008	0.733***	0.294***
	(0.041)	(0.074)	(0.043)	(0.038)	(0.047)	(0.110)	(0.070)	(0.050)	(0.059)	(0.060)	(0.054)	(0.080)	(0.043)	(0.037)	(0.036)	(0.058)	(0.049)	(0.010)	(0.057)	(0.104)	(0.014)	(0.048)	(0.024)
Medium Income	0.446**	0.167	−0.198	0.070	−0.029	−0.673	0.146	−0.466*	0.283	−0.061	0.191	−0.366	−0.216	−0.049	0.305*	0.535*	−0.096	0.011	−0.225	−0.073	0.080	0.200	0.019
	(0.153)	(0.278)	(0.161)	(0.143)	(0.177)	(0.414)	(0.263)	(0.188)	(0.224)	(0.224)	(0.202)	(0.302)	(0.161)	(0.141)	(0.134)	(0.217)	(0.183)	(0.038)	(0.214)	(0.391)	(0.052)	(0.180)	(0.091)
High Income	0.629***	0.310	−0.311	0.272	0.373	−1.595***	0.039	−0.453*	0.611*	0.189	0.709**	0.125	−0.381*	−0.132	0.271	−0.015	0.012	0.041	−0.138	0.130	0.017	−0.495*	−0.207*
	(0.175)	(0.318)	(0.184)	(0.163)	(0.202)	(0.472)	(0.300)	(0.215)	(0.255)	(0.256)	(0.231)	(0.345)	(0.184)	(0.161)	(0.153)	(0.247)	(0.208)	(0.043)	(0.245)	(0.446)	(0.060)	(0.205)	(0.103)
Sometimes rushed	0.268	0.447	0.001	0.095	−0.234	−0.241	−0.100	−0.478*	0.225	−1.013***	0.026	0.251	0.149	0.113	0.078	−0.0005	0.154	−0.111**	0.491*	−0.687	−0.037	0.455*	0.148
	(0.161)	(0.293)	(0.170)	(0.150)	(0.186)	(0.435)	(0.277)	(0.198)	(0.236)	(0.236)	(0.213)	(0.318)	(0.170)	(0.148)	(0.141)	(0.228)	(0.192)	(0.040)	(0.226)	(0.411)	(0.055)	(0.189)	(0.095)
Always rushed	0.222	0.603	0.016	0.378*	−0.141	−0.376	−0.539	−0.703**	0.457	−1.380***	0.081	0.365	0.728***	0.045	0.223	0.213	0.278	−0.119*	0.538*	−1.571**	0.008	0.555*	0.119
	(0.189)	(0.344)	(0.200)	(0.176)	(0.219)	(0.511)	(0.325)	(0.233)	(0.277)	(0.277)	(0.250)	(0.374)	(0.199)	(0.174)	(0.166)	(0.268)	(0.226)	(0.047)	(0.265)	(0.483)	(0.065)	(0.222)	(0.112)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
WT*Part-time	−0.022	0.083	0.021	−0.063	0.051	−0.011	−0.014	0.050	0.083	0.044	0.044	0.006	−0.042	−0.010	−0.019	0.126*	−0.350***	−0.006	−0.054	−0.125	−0.011	0.148**	0.072**
	(0.045)	(0.082)	(0.047)	(0.042)	(0.052)	(0.122)	(0.077)	(0.055)	(0.066)	(0.066)	(0.059)	(0.089)	(0.047)	(0.041)	(0.039)	(0.064)	(0.054)	(0.011)	(0.063)	(0.115)	(0.015)	(0.053)	(0.027)
WT*Unempl	0.048	0.066	−0.193	0.071	−0.020	0.604	−0.016	−0.261	−0.235	0.143	−0.015	−0.171	−0.184	−0.104	−0.230	−0.011	0.298	0.029	0.217	−0.091	−0.001	0.025	0.034
	(0.165)	(0.301)	(0.174)	(0.154)	(0.191)	(0.447)	(0.284)	(0.203)	(0.242)	(0.242)	(0.218)	(0.327)	(0.174)	(0.152)	(0.145)	(0.234)	(0.197)	(0.041)	(0.231)	(0.422)	(0.057)	(0.194)	(0.098)
Intercept	0.523	5.003***	−2.180***	1.616***	3.757***	47.540***	2.247***	0.531	−3.863***	11.169***	2.638***	6.322***	−0.455	−0.474	0.693*	3.441***	2.287***	0.270**	0.670	17.150***	−0.218	0.428	0.906***
	(0.386)	(0.702)	(0.407)	(0.360)	(0.446)	(1.043)	(0.663)	(0.475)	(0.564)	(0.565)	(0.510)	(0.762)	(0.406)	(0.354)	(0.338)	(0.546)	(0.460)	(0.095)	(0.540)	(0.985)	(0.132)	(0.453)	(0.228)
N	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654	3,654
R^2	0.354	0.072	0.175	0.091	0.085	0.329	0.048	0.094	0.136	0.137	0.036	0.066	0.066	0.068	0.031	0.081	0.128	0.018	0.016	0.109	0.015	0.136	0.099
Adjusted R^2	0.348	0.064	0.168	0.083	0.077	0.324	0.040	0.086	0.129	0.130	0.028	0.058	0.058	0.060	0.023	0.073	0.121	0.010	0.007	0.102	0.007	0.128	0.091

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Activity code: Commute (1), Travel (2) Food preparation (3) Personal care (4), Eating/Drinking (5), Sleep (6), Leisure (7), Reading (8), Cleaning (9), Computer/PC (10), Sport (11), Going out (12), Shopping/Services (13), Gardening (14), Pet care (15), Maintenance (16), Education (17), Religion (18), Voluntary work (19), TV/Radio (20), Elderly care (21), Child care 1(22), Child care 2(23).

Figure 3.7: *Finland, Model 2: Share of leisure per activity in percent*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
WT	14.164***	−9.521***	−3.454***	0.114	−3.557***	−10.166***	−7.835***	−1.396***	−8.389***	−1.590***	−4.471***	−1.203***	−4.834***	−2.103***	−0.565***	−3.582***	−2.705***	−0.136	−0.608*	−4.034***	−0.893***	−2.650***	−0.583**
	(0.343)	(0.504)	(0.336)	(0.255)	(0.512)	(0.684)	(0.648)	(0.271)	(0.492)	(0.395)	(0.403)	(0.282)	(0.337)	(0.316)	(0.136)	(0.389)	(0.326)	(0.139)	(0.269)	(0.714)	(0.213)	(0.356)	(0.179)
WT^2	−0.885***	0.206***	0.019	−0.052*	−0.065	−0.009	0.182**	0.006	0.214***	−0.062	0.150***	0.033	0.090**	0.024	0.024	0.082*	0.144***	−0.002	−0.006	−0.158*	0.013	0.065	−0.011
	(0.032)	(0.048)	(0.032)	(0.024)	(0.048)	(0.065)	(0.061)	(0.026)	(0.046)	(0.037)	(0.038)	(0.027)	(0.032)	(0.030)	(0.013)	(0.037)	(0.031)	(0.013)	(0.025)	(0.067)	(0.020)	(0.034)	(0.017)
Part-time	1.766	−6.444***	6.006***	1.574	−3.658	−10.301***	8.897***	−0.655	2.051	−0.817	−4.206**	−1.001	−6.114***	−2.878*	−0.430	−6.192***	17.951***	0.224	2.471*	−3.519	−0.995	4.198**	2.071**
	(1.330)	(1.957)	(1.305)	(0.990)	(1.987)	(2.654)	(2.516)	(1.051)	(1.910)	(1.533)	(1.563)	(1.094)	(1.310)	(1.225)	(0.529)	(1.509)	(1.265)	(0.539)	(1.043)	(2.772)	(0.828)	(1.381)	(0.695)
Unempl	−6.634***	−0.820	7.297***	0.145	−10.612***	−15.648***	10.242***	−0.624	−5.018*	15.136***	−1.381	−3.854**	−4.050*	−2.871	1.687**	−4.192*	−9.866***	2.915***	−2.328	31.037***	1.295	−1.468	−0.387
	(1.605)	(2.361)	(1.574)	(1.194)	(2.396)	(3.201)	(3.035)	(1.268)	(2.304)	(1.849)	(1.885)	(1.319)	(1.580)	(1.478)	(0.638)	(1.821)	(1.526)	(0.650)	(1.258)	(3.344)	(0.999)	(1.666)	(0.838)
Age	−0.166***	−0.014	0.585***	0.054*	0.334***	−0.773***	−0.346***	0.513***	0.665***	−0.629***	−0.078	−0.075**	0.234***	0.384***	0.084***	0.225***	−0.717***	0.056***	0.177***	0.170*	0.078***	−0.629***	−0.130***
	(0.035)	(0.052)	(0.035)	(0.026)	(0.053)	(0.070)	(0.067)	(0.028)	(0.051)	(0.041)	(0.041)	(0.029)	(0.035)	(0.032)	(0.014)	(0.040)	(0.033)	(0.014)	(0.028)	(0.073)	(0.022)	(0.037)	(0.018)
Gender	−4.731***	−2.006	30.791***	8.908***	−8.529***	3.123*	−4.543**	2.491***	37.856***	−15.188***	−5.785***	−0.958	5.787***	−10.102***	0.175	−20.470***	−1.159	0.289	−2.584***	−27.550***	−2.506***	14.464***	2.227***
	(0.779)	(1.146)	(0.764)	(0.580)	(1.163)	(1.554)	(1.473)	(0.615)	(1.118)	(0.898)	(0.915)	(0.640)	(0.767)	(0.717)	(0.310)	(0.884)	(0.741)	(0.316)	(0.611)	(1.623)	(0.485)	(0.808)	(0.407)
Completed 2ary Education	−0.747	6.895***	−1.295	−1.154	7.672***	−2.690	−10.399***	5.276***	0.649	1.802	1.499	0.427	4.261***	−0.191	−0.970*	−1.452	0.850	0.004	2.622**	−17.942***	−0.078	3.430**	1.535**
	(1.058)	(1.556)	(1.038)	(0.787)	(1.579)	(2.110)	(2.000)	(0.835)	(1.518)	(1.219)	(1.242)	(0.869)	(1.041)	(0.974)	(0.420)	(1.200)	(1.006)	(0.428)	(0.829)	(2.204)	(0.659)	(1.098)	(0.552)
Above 2ary education	−3.250**	12.150***	−3.407**	−4.131***	8.344***	−8.895***	−12.214***	16.528***	−1.352	5.264***	6.949***	3.956***	5.286***	−3.847***	−2.937***	−4.838***	3.099**	0.327	5.973***	−37.892***	0.145	10.214***	4.526***
	(1.242)	(1.827)	(1.218)	(0.924)	(1.854)	(2.476)	(2.348)	(0.981)	(1.782)	(1.431)	(1.458)	(1.021)	(1.222)	(1.143)	(0.494)	(1.409)	(1.181)	(0.503)	(0.973)	(2.587)	(0.773)	(1.289)	(0.649)
HH size	−0.212	1.427**	2.435***	−1.860***	−0.653	−1.821**	−4.041***	−1.409***	2.612***	−3.106***	−0.978**	−1.141***	−0.561	0.474	−1.076***	2.095***	−1.829***	0.584***	−0.468	−3.353***	−0.559**	9.570***	3.872***
	(0.316)	(0.465)	(0.310)	(0.235)	(0.472)	(0.630)	(0.597)	(0.250)	(0.454)	(0.364)	(0.371)	(0.260)	(0.311)	(0.291)	(0.126)	(0.358)	(0.300)	(0.128)	(0.248)	(0.658)	(0.197)	(0.328)	(0.165)
Medium Income	−0.526	−1.540	−1.852	−0.803	9.117***	−1.813	−5.629**	2.696**	2.158	1.515	−1.763	1.284	2.512*	1.386	0.577	0.611	−7.088***	−1.510***	0.892	−2.720	1.547*	0.721	0.228
	(1.117)	(1.644)	(1.096)	(0.832)	(1.669)	(2.229)	(2.113)	(0.883)	(1.604)	(1.288)	(1.313)	(0.919)	(1.100)	(1.029)	(0.444)	(1.268)	(1.063)	(0.453)	(0.876)	(2.329)	(0.696)	(1.160)	(0.584)
High Income	2.143	2.511	−3.882**	−1.021	13.235***	0.664	−10.406***	3.475***	1.828	2.168	0.739	3.970***	2.905*	1.907	0.069	−0.200	−6.741***	−2.189***	1.914	−9.546***	0.119	−2.532	−1.129
	(1.295)	(1.905)	(1.270)	(0.964)	(1.934)	(2.583)	(2.449)	(1.023)	(1.859)	(1.492)	(1.521)	(1.065)	(1.275)	(1.193)	(0.515)	(1.469)	(1.231)	(0.525)	(1.015)	(2.698)	(0.806)	(1.344)	(0.676)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	(2.242)	(3.299)	(2.200)	(1.669)	(3.348)	(4.472)	(4.240)	(1.771)	(3.219)	(2.584)	(2.634)	(1.843)	(2.208)	(2.065)	(0.891)	(2.544)	(2.132)	(0.908)	(1.758)	(4.673)	(1.396)	(2.327)	(1.171)
WT*Part-time	−1.172***	0.832**	−0.855***	−0.408*	0.652*	2.681***	−0.631	0.115	−0.058	−0.051	0.397	0.106	0.707***	0.186	−0.005	0.567*	−1.746***	0.012	−0.263	−0.593	0.210	−0.387	−0.298**
	(0.218)	(0.321)	(0.214)	(0.162)	(0.326)	(0.435)	(0.412)	(0.172)	(0.313)	(0.251)	(0.256)	(0.179)	(0.215)	(0.201)	(0.087)	(0.247)	(0.207)	(0.088)	(0.171)	(0.454)	(0.136)	(0.226)	(0.114)
WT*Unempl	−2.903***	2.245*	0.096	0.002	2.875**	3.971***	−2.121	0.694	0.952	−1.663*	0.126	0.245	1.434*	−0.068	−0.213	−0.385	0.938	−0.094	0.044	−5.412***	−0.494	−0.317	0.048
	(0.605)	(0.890)	(0.593)	(0.450)	(0.903)	(1.207)	(1.144)	(0.478)	(0.868)	(0.697)	(0.711)	(0.497)	(0.596)	(0.557)	(0.240)	(0.686)	(0.575)	(0.245)	(0.474)	(1.261)	(0.377)	(0.628)	(0.316)
Intercept	10.558***	60.367***	−14.354***	14.224***	140.559***	599.618***	156.322***	−12.036***	−21.531***	87.549***	61.308***	18.625***	−5.962	8.750**	6.189***	37.653***	43.212***	−0.583	1.895	210.222***	2.761	3.464	1.190
	(3.166)	(4.657)	(3.106)	(2.356)	(4.727)	(6.314)	(5.986)	(2.501)	(4.544)	(3.648)	(3.718)	(2.602)	(3.117)	(2.916)	(1.258)	(3.592)	(3.010)	(1.282)	(2.482)	(6.597)	(1.971)	(3.286)	(1.654)
N	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086
R^2	0.270	0.159	0.220	0.036	0.097	0.179	0.142	0.072	0.205	0.072	0.087	0.031	0.124	0.063	0.023	0.070	0.075	0.011	0.016	0.123	0.015	0.143	0.073
Adjusted R^2	0.268	0.157	0.218	0.034	0.095	0.177	0.140	0.070	0.203	0.070	0.085	0.029	0.123	0.061	0.021	0.068	0.074	0.009	0.014	0.122	0.013	0.141	0.072

Note: *p<0.05; **p<0.01; ***p<0.001

Activity code: Commute (1), Travel (2) Food preparation (3) Personal care (4), Eating/Drinking (5), Sleep (6), Leisure (7), Reading (8), Cleaning (9), Computer/PC (10), Sport (11), Going out (12), Shopping/Services (13), Gardening (14), Pet care (15), Maintenance (16), Education (17), Religion (18), Voluntary work (19), TV/Radio (20), Elderly care (21), Child care 1(22), Child care 2(23).

Figure 3.8: *France, Model 1: Absolute duration per activity in minutes*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
WT	1.238***	−0.441***	−0.024	0.144***	0.153***	0.485***	−0.264***	−0.042	−0.345***	0.010	−0.223***	−0.052*
	(0.032)	(0.039)	(0.027)	(0.022)	(0.042)	(0.058)	(0.051)	(0.022)	(0.038)	(0.031)	(0.030)	(0.022)
WT^2	−0.058***	−0.001	−0.011***	0.005**	0.007	0.096***	−0.001	−0.001	−0.001	−0.011***	0.005	0.0003
	(0.003)	(0.004)	(0.003)	(0.002)	(0.004)	(0.006)	(0.005)	(0.002)	(0.004)	(0.003)	(0.003)	(0.002)
Part-time	0.188	−0.445**	0.337**	0.097	−0.193	−0.789***	0.615**	−0.034	0.067	0.003	−0.271*	−0.061
	(0.123)	(0.150)	(0.103)	(0.085)	(0.165)	(0.226)	(0.198)	(0.085)	(0.147)	(0.121)	(0.118)	(0.085)
Unempl	−0.386**	−0.047	0.473***	−0.029	−0.625**	−1.170***	0.645**	0.029	−0.345	1.061***	−0.085	−0.242*
	(0.149)	(0.181)	(0.125)	(0.102)	(0.199)	(0.273)	(0.239)	(0.102)	(0.178)	(0.147)	(0.142)	(0.102)
Age	−0.014***	−0.002	0.046***	0.005*	0.030***	−0.060***	−0.029***	0.041***	0.052***	−0.050***	−0.007*	−0.006**
	(0.003)	(0.004)	(0.003)	(0.002)	(0.004)	(0.006)	(0.005)	(0.002)	(0.004)	(0.003)	(0.003)	(0.002)
Gender	−0.453***	−0.117	2.491***	0.782***	−0.797***	0.262*	−0.364**	0.201***	3.031***	−1.259***	−0.451***	−0.076
	(0.072)	(0.088)	(0.060)	(0.050)	(0.097)	(0.132)	(0.116)	(0.050)	(0.086)	(0.071)	(0.069)	(0.050)
Completed 2ary Education	−0.037	0.516***	−0.117	−0.105	0.603***	−0.144	−0.842***	0.402***	0.036	0.151	0.089	−0.002
	(0.098)	(0.119)	(0.082)	(0.067)	(0.131)	(0.180)	(0.157)	(0.067)	(0.117)	(0.097)	(0.094)	(0.067)
Above 2ary education	−0.222	0.958***	−0.286**	−0.379***	0.663***	−0.558**	−1.006***	1.351***	−0.115	0.431***	0.505***	0.274***
	(0.115)	(0.140)	(0.096)	(0.079)	(0.154)	(0.211)	(0.185)	(0.079)	(0.138)	(0.113)	(0.110)	(0.079)
HH size	−0.012	0.130***	0.175***	−0.161***	−0.054	−0.129*	−0.328***	−0.120***	0.188***	−0.242***	−0.089**	−0.093***
	(0.029)	(0.036)	(0.025)	(0.020)	(0.039)	(0.054)	(0.047)	(0.020)	(0.035)	(0.029)	(0.028)	(0.020)
Medium Income	0.017	−0.155	−0.147	−0.098	0.741***	−0.247	−0.379*	0.215**	0.194	0.094	−0.129	0.097
	(0.104)	(0.126)	(0.087)	(0.071)	(0.138)	(0.190)	(0.166)	(0.071)	(0.124)	(0.102)	(0.099)	(0.071)
High Income	0.293*	0.160	−0.318**	−0.124	1.082***	−0.014	−0.859***	0.300***	0.188	0.117	0.062	0.351***
	(0.120)	(0.146)	(0.101)	(0.082)	(0.160)	(0.220)	(0.193)	(0.083)	(0.143)	(0.118)	(0.115)	(0.083)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
WT*Part-time	−0.146***	0.056*	−0.050**	−0.037**	0.050	0.279***	−0.017	0.006	0.019	−0.030	0.023	0.006
	(0.020)	(0.025)	(0.017)	(0.014)	(0.027)	(0.037)	(0.032)	(0.014)	(0.024)	(0.020)	(0.019)	(0.014)
WT*Unempl	−0.351***	0.201**	0.025	0.005	0.226**	0.368***	−0.104	0.040	0.057	−0.128*	0.017	0.006
	(0.056)	(0.068)	(0.047)	(0.039)	(0.075)	(0.103)	(0.090)	(0.039)	(0.067)	(0.055)	(0.054)	(0.039)
Intercept	0.780**	4.088***	−1.659***	2.883***	9.583***	41.920***	11.535***	−1.138***	−2.316***	6.811***	4.488***	1.383***
	(0.293)	(0.357)	(0.246)	(0.202)	(0.392)	(0.538)	(0.471)	(0.202)	(0.351)	(0.289)	(0.281)	(0.202)
N	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086
R^2	0.331	0.104	0.165	0.075	0.053	0.385	0.080	0.061	0.161	0.058	0.064	0.025
Adjusted R^2	0.329	0.102	0.163	0.073	0.051	0.384	0.078	0.059	0.159	0.056	0.062	0.023

	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
WT	−0.228***	−0.094***	−0.023*	−0.192***	−0.174***	−0.004	−0.016	0.235***	−0.048**	−0.090**	−0.005
	(0.026)	(0.023)	(0.011)	(0.029)	(0.024)	(0.010)	(0.021)	(0.059)	(0.016)	(0.028)	(0.014)
WT^2	−0.001	−0.002	0.001	0.002	0.009***	−0.001	−0.001	−0.031***	−0.0004	−0.0004	−0.003
	(0.002)	(0.002)	(0.001)	(0.003)	(0.002)	(0.001)	(0.002)	(0.006)	(0.001)	(0.003)	(0.001)
Part-time	−0.452***	−0.189*	−0.031	−0.417***	1.279***	0.018	0.183*	−0.257	−0.075	0.281**	0.146**
	(0.101)	(0.091)	(0.043)	(0.112)	(0.092)	(0.040)	(0.081)	(0.228)	(0.061)	(0.107)	(0.055)
Unempl	−0.320**	−0.192	0.110*	−0.305*	−0.697***	0.201***	−0.134	2.092***	0.082	−0.093	−0.023
	(0.121)	(0.110)	(0.052)	(0.135)	(0.111)	(0.048)	(0.098)	(0.275)	(0.074)	(0.129)	(0.067)
Age	0.018***	0.029***	0.006***	0.017***	−0.052***	0.004***	0.014***	0.015*	0.006***	−0.051***	−0.010***
	(0.003)	(0.002)	(0.001)	(0.003)	(0.002)	(0.001)	(0.002)	(0.006)	(0.002)	(0.003)	(0.001)
Gender	0.467***	−0.777***	0.018	−1.558***	−0.082	0.018	−0.199***	−2.273***	−0.179***	1.143***	0.173***
	(0.059)	(0.053)	(0.025)	(0.066)	(0.054)	(0.023)	(0.048)	(0.133)	(0.036)	(0.063)	(0.032)
Completed 2ary Education	0.310***	−0.008	−0.077*	−0.110	0.063	−0.007	0.228***	−1.318***	−0.005	0.260**	0.114**
	(0.080)	(0.072)	(0.034)	(0.089)	(0.073)	(0.032)	(0.065)	(0.181)	(0.049)	(0.085)	(0.044)
Above 2ary education	0.389***	−0.316***	−0.245***	−0.405***	0.243**	0.024	0.505***	−3.005***	0.004	0.827***	0.362***
	(0.094)	(0.085)	(0.040)	(0.105)	(0.086)	(0.037)	(0.076)	(0.213)	(0.057)	(0.100)	(0.051)
HH size	−0.055*	0.036	−0.090***	0.163***	−0.138***	0.046***	−0.034	−0.255***	−0.041**	0.787***	0.317***
	(0.024)	(0.022)	(0.010)	(0.027)	(0.022)	(0.009)	(0.019)	(0.054)	(0.014)	(0.025)	(0.013)
Medium Income	0.159	0.120	0.051	0.056	−0.509***	−0.119***	0.069	−0.202	0.108*	0.052	0.013
	(0.085)	(0.076)	(0.036)	(0.094)	(0.077)	(0.034)	(0.068)	(0.191)	(0.051)	(0.090)	(0.046)
High Income	0.188	0.167	0.004	−0.038	−0.488***	−0.175***	0.165*	−0.765***	0.006	−0.207*	−0.096
	(0.098)	(0.089)	(0.042)	(0.109)	(0.090)	(0.039)	(0.079)	(0.222)	(0.059)	(0.104)	(0.054)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
WT*Part-time	0.050**	0.008	−0.002	0.031	−0.121***	0.003	−0.020	−0.075*	0.018	−0.025	−0.024**
	(0.016)	(0.015)	(0.007)	(0.018)	(0.015)	(0.007)	(0.013)	(0.037)	(0.010)	(0.018)	(0.009)
WT*Unempl	0.143**	−0.011	−0.012	−0.043	0.066	0.001	−0.014	−0.410***	−0.037	−0.045	0.0003
	(0.046)	(0.041)	(0.019)	(0.051)	(0.042)	(0.018)	(0.037)	(0.104)	(0.028)	(0.049)	(0.025)
Intercept	−0.556*	0.528*	0.454***	2.715***	3.104***	−0.064	0.039	15.244***	0.171	0.048	−0.042
	(0.239)	(0.216)	(0.102)	(0.267)	(0.219)	(0.095)	(0.193)	(0.542)	(0.145)	(0.255)	(0.131)
N	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086	15,086
R^2	0.094	0.060	0.018	0.064	0.073	0.010	0.013	0.067	0.014	0.142	0.067
Adjusted R^2	0.092	0.058	0.016	0.062	0.071	0.008	0.011	0.065	0.012	0.140	0.066

Note: $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

Activity code: Commute (1), Travel (2) Food preparation (3) Personal care (4), Eating/Drinking (5), Sleep (6), Leisure (7), Reading (8), Cleaning (9), Computer/PC (10), Sport (11), Going out (12), Shopping/Services (13), Gardening (14), Pet care (15), Maintenance (16), Education (17), Religion (18), Voluntary work (19), TV/Radio (20), Elderly care (21), Child care 1(22), Child care 2(23).

Figure 3.9: *France, Model 2: Share of leisure per activity in percent*

Appendix 3.E Activities and their energy use

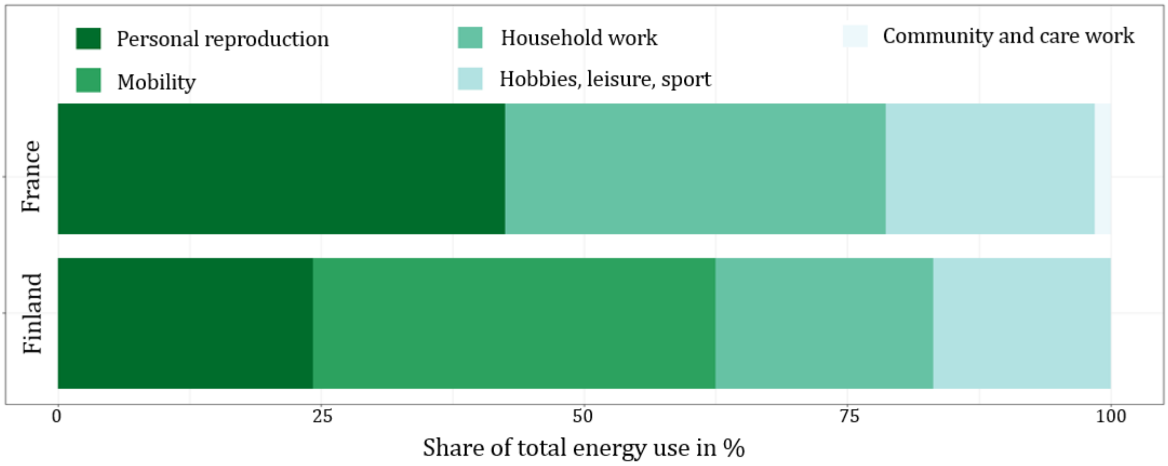
Table 3.4: Energy use intensities of different activities for France and Finland

Activities Finland	**kWh/h**	**Activities France**	**kWh/h**
Free time trips	35.69	Housework: meals	7.21
Trips to work and study	32.64	Sport and outings	5.73
Eating	15.04	Personal time	5.65
Shopping, Services, Public administration and related	12.27	Shopping and administration	5.09
Phone conversations	10.26	Housework: clothes	3.28
Personal hygiene and dressing	7.66	Housework: home	1.51
Housework	5.61	Work and study	1.47
Maintenance, gardening, pets	5.23	Leisure (energy-int.)	1.39
Culture events	4.59	Eating at home	0.92
Reading	1.41	Leisure (non-energy-int.)	0.91
Hobbies	1.35	Eating out	0.80
Studying	1.02	Care (for others)	0.79
Television	0.94	Sleep	0.77
Sports and recreation	0.82		

Note:Energy use for France corresponds to direct energy, numbers for Finland include direct and indirect (embodied) energy use. Source: Jalas & Juntunen (2015) and de Lauretis et al. (2017).

Appendix 3.F Sources of energy use by activity

Figure 3.10: Sources of energy use by activity



Note: Care work is not included for Finland, as no energy use values were available. Mobility is treated as an ancillary activity in France and already allocated to all out of home activities.

Chapter 4

Agentizing a general equilibrium model of environmental tax reform

4.1 Introduction

A low-carbon transition in line with the targets of the Paris agreement requires deep transformations of our current modes of production and consumption. These will likely lead to considerable dynamics and entail extensive distributional impacts. Climate policies are often modelled in general equilibrium (GE) settings with representative agents and immediate market clearing, entailing restrictive assumptions to assure analytical tractability. Here we explore the use of agent-based models (ABMs) as they allow relieving some of these limiting assumptions. In particular, they are well-equipped to study the role of agent heterogeneity, social networks and transition dynamics that emerge from the resulting interactions (Farmer et al., 2015). Yet, while the literature on ABMs for climate policy is growing, the method has received limited attention in assessing ETRs (Castro et al., 2020).

Environmental tax reforms have been extensively discussed and modelled in public and environmental economics (see e.g. Pearce, 1991 for the original idea, Goulder, 1995; Bovenberg, 1999; Bosello et al., 2001 for earlier reviews or Freire-González, 2018 or Maxim and Zander, 2019 for more recent meta analyses focused on modelling). While the literature on this topic is vast and a number of different models are applied to study potential impacts of ETRs, agent-based approaches in this context are sparse. To the best of our knowledge, the only studies addressing revenue use of carbon taxation through agent-based models are Gerst et al. (2013) and Rengs et al. (2020).

This study aims to build a bridge between general equilibrium and agent-based modelling in order to explore differences and similarities using a concrete policy example. Specifically, we are using an agent-based approach to replicate a recent static general equilibrium model by Aubert and Chiroleu-Assouline (2019) which studies effects of an environmental tax reform, a shift from labour taxes to carbon taxes. For convenience we will refer to this paper as A&CA. Following the semantics of Guerrero and Axtell (2011), we call the process of rendering a neoclassical model into an agent-based model *agentization*.

In general, replication of a simple model is easier. However, as the long-term goal is to build a more comprehensive ETR-ABM that can be related to the GEM literature, we still chose to replicate the relatively complex model by A&CA. It features several characteristics that are particularly relevant for studying ETR. This includes some level of heterogeneity between households in the form of high and low income, a subsistence level of polluting consumption, which is relevant for distributional concerns, as well as an imperfect low-wage labour market with a search-and-matching process. Beyond their relevance for policy design, household heterogeneity and probabilistic search processes are two characteristics that can be modelled especially well with an agent-based approach. While the focus of their study is theoretical, A&CA also provide a numerical illustration of their model. This is an additional advantage, because it allows us to reproduce their simulations with our ABM using mostly identical parameter values.

Similarly to the original paper, our study explores the conditions for a 'double dividend', a simultaneous increase in consumption welfare and environmental quality, when carbon tax revenues are recycled through labour tax cuts. A&CA also address the redistributional potential of an ETR. Frictions between efficiency and equity goals are highly relevant in current discussions of carbon taxation and its acceptability (Klenert et al., 2018). One main feature of A&CA's model is the distinction between low- and high-wage labour, operating in different labour markets, where the low-wage labour market exhibits frictions through a search and matching process. Another important characteristic is the positive subsistence level of polluting consumption, captured through a *Stone-Geary* preference structure.

The contribution of our study is three-fold. First, we present a basic ABM for environmental tax reforms that can be used to study various research questions in the future. Second, relating this model to a general equilibrium framework allows for a direct methodological comparison between the two modelling approaches, which we hope will facilitate the dialogue between different modelling communities. Third, our study can be seen as a robustness check of the policy insights of A&CA.

The remainder of the article is organised as follows. Section 4.2.1 presents the main characteristics and assumptions of the GE model and how our agent-based approach differs from these. Section 4.2.2 provides an overview of the ABM sequence, its key equations and parameters. Results are presented in Section 4.3, structured according to six propositions in the original study by Aubert and Chiroleu-Assouline. Section 4.4 discusses the methodological challenges and lessons learnt from the agentization exercise. Section 4.5 concludes.

4.2 The model structure

This section describes the agent-based model and its connection with the general equilibrium model it aims to replicate. Section 2.1 discusses the key assumptions underlying the GE model as well as whether and how they were translated into the ABM. Section 2.2 presents the different steps of the ABM sequence in more detail.

4.2.1 Key assumptions

This section introduces the central assumptions of both models. The GEM describes one representative firm producing two consumption goods (C = clean and D = dirty), with two inputs (high- and low-wage labour).[1] A clean public good, G, is also provided. This public good is assumed to be exogenously fixed, so that it affects the overall utility level, but not its variation due to the tax reform (A&CA, p.71). In the ABM, tax revenue fluctuates because of variations in unemployment, so G has to vary to keep the government budget balanced.

Households in the GEM choose between consumption and leisure. The labour-leisure choice is particular in the underlying GEM in that it is modeled differently for low- and high-wage households. Low-wage workers will not have any leisure if they are employed. Only unemployed low-wage workers "enjoy" leisure. High-wage workers, on the other hand, can set their labour supply at the intensive margin, so disutility of work enters their labour decision through an effort cost function. Following A&CA, this effort cost is defined as:

$$\phi(h) = \frac{h^{1+\frac{1}{\eta_H}}}{1+\frac{1}{\eta_H}} \tag{4.1}$$

where effort cost, $\phi(h)$, is increasing labour supply h. η_H reflects the Frisch elasticity of high-wage labour supply.

Wage setting differs in the ABM, compared to the GEM. In the original model, the economy is assumed to be in equilibrium, so wage rates are at their optimal level. The high-wage rate equals the marginal product of high-wage labour. The low-wage rate follows the Nash-optimum resulting from a bargaining process between workers and firm splitting the rent from the job creation. That means the wage rate lies below the marginal productivity of low-wage labour. In the ABM fluctuations around a stable state are approached over the course of many model rounds through incremental adjustment of low- and high-wage rates.

[1] Analogous to the terms high- and low-*skilled* labour in A&CA.

Another difference between the approaches is linked to these fluctuations and adjustment processes. It is a requirement of the ABM to be stock-flow consistent. Stock-flow consistency (SFC) refers to a rigorous accounting framework of all stocks and flows in the model economy. Accounting for flows is different in a dynamic ABM, compared to a static GEM in equilibrium. One has to make assumptions about what happens to all monetary flows at all times. This includes potential profits during the initialization (*burn-in*) or during transition phases, the vacancy cost and government spending. Our assumption is that vacancy costs and profits are distributed equally among all households through a per capita dividend, and government spending always equals net government revenue. Figure 4.1 illustrates the monetary flows between agents. In addition to specifying wage and tax payments, private consumption and benefits, the ABM has to clarify what happens to profits, vacancy costs and government spending[2]. We thus interpret the "clean public good" as additional demand for the clean good, C. Public services, even those with least environmental impact, usually rely on intermediate goods produced by private firms. These additional flows are marked as black arrows, whereas the grey arrows represent flows that have already been highlighted by A&CA.

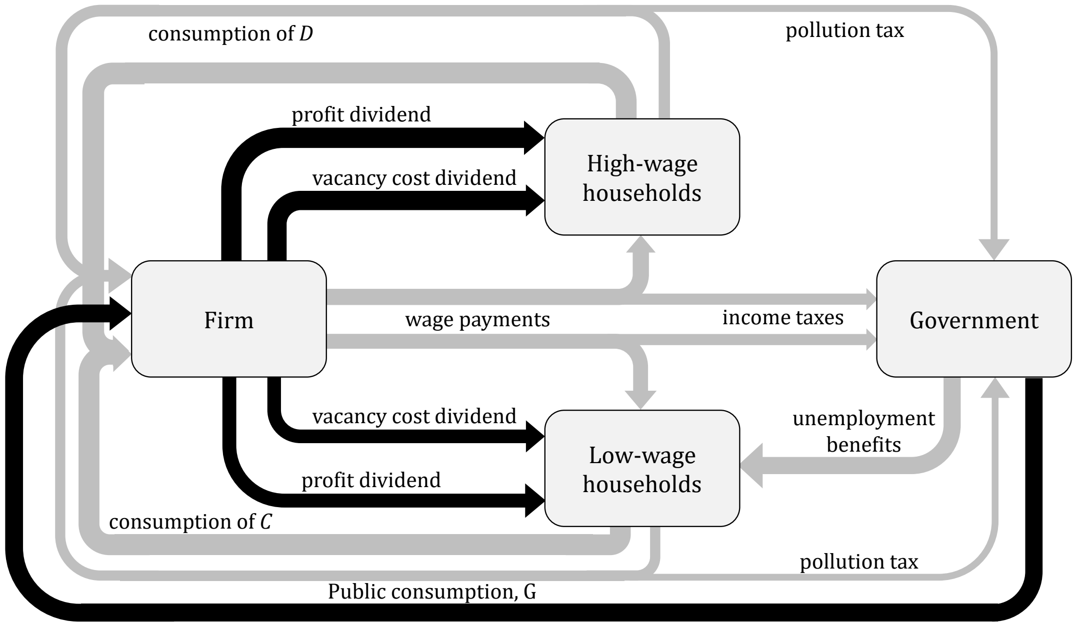


Figure 4.1: Stock-flow consistent monetary flows between agents in the ABM

Note: Grey arrows indicate monetary flows already highlighted in the GEM, while black arrows point to additional monetary flows identified as relevant for an ABM. Size of the arrows indicates relative size of the flow.

As there are more agents in the ABM than in the GEM, the matching function, i.e. the probability for low-wage workers to match with job offers, needs to be adjusted. The GEM assumes a representable mass of low-wage workers equal to one with a certain probability of being (un)employed

[2]Note that in the GEM the marginal cost of a vacancy should equal the job rent exactly in equilibrium, such that profits are zero (A&CA, p.65). In this case assumptions about profit flows are redundant.

while the ABM is populated by 1000 (N_L) low-wage workers. As the matching probability in the new function can increase above 1, we have to impose an additional condition. If the optimal number of vacancies a firm chooses to set means that the matching probability will be outside its defined range between zero and one, the firm compares the expected profits from all possible vacancy postings, and chooses the number of vacancies that is expected to yield the highest profits.[3] A brief summary of similarities and differences between the two approaches is offered in Table 4.1.

Table 4.1: Comparison of model assumptions between GEM and ABM

		General equilibrium model	Agent-based model
Identical	Number of firms	1	
	Goods	Clean (C), dirty (D), public (G)	
	Production technology	$F(L,H) = L^{\alpha}H^{1-\alpha}$	
	Labour-leisure choice	Leisure for unemployed low-wage HHs Effort cost function for high-wage HHs	
	Low-wage labour market	Search and matching	
	High-wage labour market	Perfect competition	
	Price of consumption	$p_c = p_d = p_y$	
	Household preferences	$Q_{i,t} = C_{it}^{1-\sigma}(D_{it} - \bar{D})^{\sigma}$	
Distinct	Number of households	2	1,460
	Matching function	$\omega v^{1-\xi}1^{\xi}$	$\omega v^{1-\xi}N_L^{\xi}$
	Clean public good, G	Fixed amount	Changing, modelled as demand for good C
	Stock & flow accounting	Unclear	Stock-flow consistent
	Wage-setting	Derive optimum	Approaching optimum gradually over time
	Tax rate change	Infinitesimally small	0.01%

4.2.2 The agent-based model

After the agent-based model is initialized, a sequence of actions, referred to as a *model round*, follows. Figure 4.2 displays the sequence of decisions and transactions in the model, which we will now describe in more detail.[4]

1. *Taxation*

   The government determines and announces income and pollution tax rates for the current period $\tau_{D,t}$, $\tau_{H,t}$ and $\tau_{L,t}$. Total government expenditure is defined as[5]:

$$G + (N_L - L_t)B_t = L_t w_{L,t}\tau_{L,t} + H_t w_{H,t}\tau_{H,t} + \tau_{D,t}p_y D_{tot,t} \quad (4.2)$$

   where G is public spending on a clean good, $(N_L - L_t)B_t$ is the total amount of unemployment

[3]The lower bound of the probability function is given through $\omega^{\frac{1}{\xi}}N_L$ and the maximum $\left(\frac{N_L^{1-\xi}}{\omega}\right)^{\frac{1}{1-\xi}}$.

[4]*Notation.* t always refers to the current model round, t_0 refers to the no-policy scenario. i denotes an individual household and j the type of good (C or D). τ is reserved for tax rates.

[5]Equal to the government budget constraint in A&CA (their Eq.(11)), except for the number of agents and the dynamic element t.

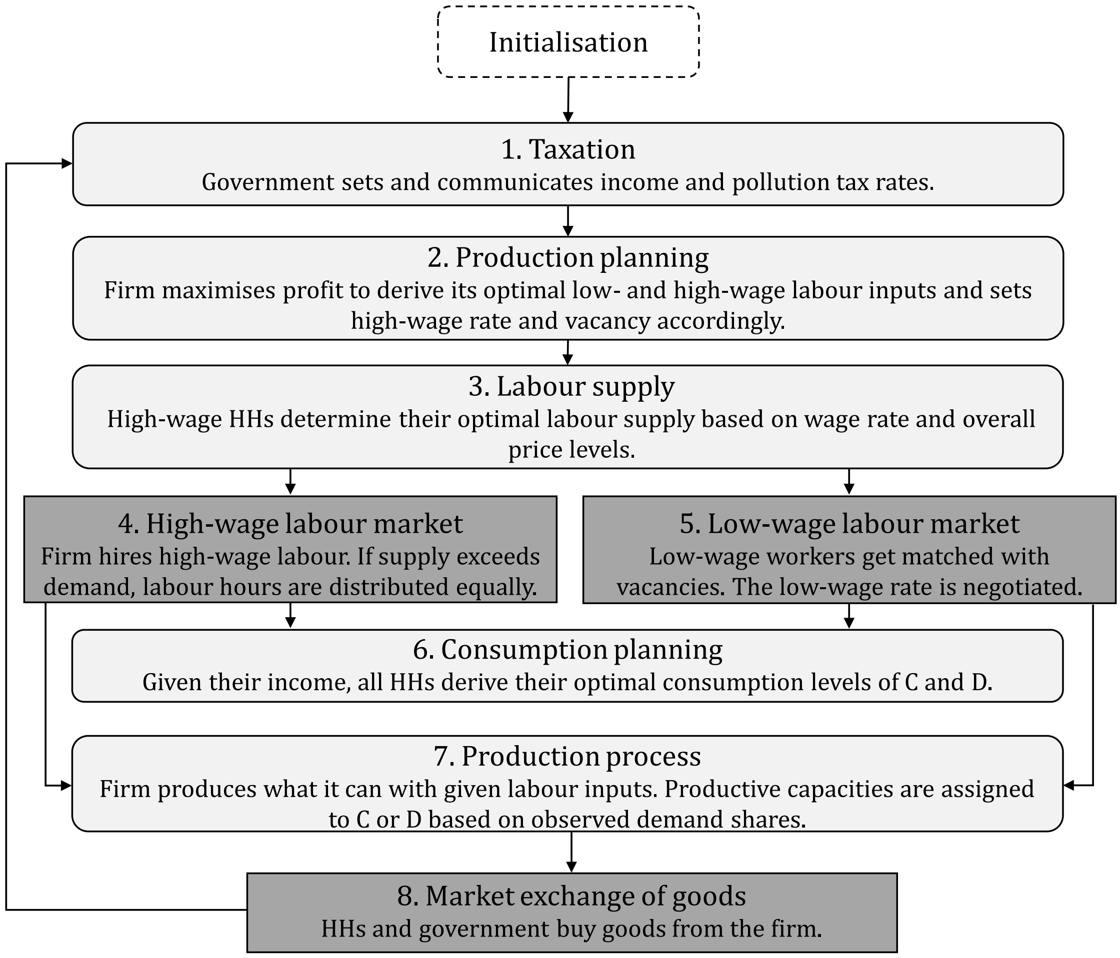


Figure 4.2: Structure and sequence of the model

Note: Dark boxes indicate a market interaction between firm and households, light boxes indicate agent-internal decision processes.

benefits to be paid. The right hand side reflects government revenues. L_t and H_t are the amount of low- and high-wage labour input, $w_{L,t}$ and $w_{H,t}$ are the low- and high-wage rates, $\tau_{L,t}$, $\tau_{H,t}$ and $\tau_{D,t}$ are the tax rates on low- and high-wage income as well as polluting consumption, and $D_{tot,t}$ is the total consumption of the polluting good, D.

When a revenue-neutral pollution tax is implemented, the government calculates expected tax revenues and adjusts the income tax rates downwards to balance out the effect. The income tax revenue without a pollution tax is defined as:

$$TR_{inc,0} = \tau_{H,t_0} w_{H,t_0} H_{t_0} + \tau_{L,t_0} w_{L,t_0} L_{t_0} \tag{4.3}$$

The expected tax revenues from the pollution tax based on sales of good D in the previous period are defined as:

$$TR_{poll,t} = \tau_{D,t} p_y D_{tot,t-1} \tag{4.4}$$

Expected wage incomes of high- and low-wage households based on previously realized labour are defined as:

$$WI_{H,t}^{exp} = w_{H,t-1}H_{t-1} \tag{4.5}$$

$$WI_{L,t}^{exp} = w_{L,t-1}L_{t-1} \tag{4.6}$$

The government sets $\tau_{H,t}$ and $\tau_{L,t}$ according to the following rules[6]:

$$\tau_{H,t} = \frac{TR_{inc,0} - TR_{poll,t}}{WI_{H,t}^{exp} + (1-\gamma)\frac{\tau_{L,t_0}}{\tau_{H,t_0}}WI_{L,t}^{exp}} \tag{4.7}$$

$$\tau_{L,t} = (1-\gamma)\tau_{H,t}\frac{\tau_{L,t_0}}{\tau_{H,t_0}} \tag{4.8}$$

Like in the GEM γ, $\epsilon[0,1)$, is a redistribution parameter. When set to zero, the tax revenues are recycled proportionately to high- and low-wage workers, while a higher γ raises the progressivity of the tax reform by increasing the tax cuts for low-wage, relative to high-wage labour. Since the calculations are based on the values of the previous period, this results in a transition path towards a balanced government budget.

2. *Production planning*

The firm updates its high-wage rate ($w_{H,t}$), taking into account the marginal productivity of high-wage labour in the previous round ($MP_{H,t-1}$):

$$MP_{H,t-1} = \begin{cases} (1-\alpha)\left[\frac{L_{t-1}}{H_{t-1}}\right]^{\alpha} & \text{if } H_{t-1} > 0 \\ 0 & \text{otherwise.} \end{cases} \tag{4.9}$$

If no high-wage labour is used in production ($H_{t-1} = 0$), we define the marginal product to be zero for practical reasons. In this case, the high-wage rate is not adjusted (case 1 below). If demand for high-wage labour exceeds supply ($H_{t-1}^{opt} > H_{t-1}^{S}$), the wage rate is increased by $X\%$ (case 2 below) and, vice versa. However, the wage is never increased to more than the observed marginal product of high-wage labour (case 3). Thus, the new wage rate is defined as:

$$w_{H,t} = \begin{cases} w_{H,t-1} & \text{if } MP_{H,t-1} = 0, \\ (1+X)w_{H,t-1} & \text{if } MP_{H,t-1} > (1+X)w_{H,t-1} \text{ and } H_{t-1}^{opt} > H_{t-1}^{S}, \\ MP_{H,t-1} & \text{if } 0 < MP_{H,t-1} \leqslant (1+X)w_{H,t-1} \text{ and } H_{t-1}^{opt} > H_{t-1}^{S}, \\ (1-X)w_{H,t-1} & \text{otherwise.} \end{cases} \tag{4.10}$$

[6]See Appendix 4.A for labour tax variation in A&CA.

Based on the new high-wage rate ($w_{H,t}$) the firm maximises its expected profit Π_t with respect to high-wage labour and low-wage vacancies. The expected profit function is identical to the GEM, except that the value of the low-wage rate is based on the previous round ($w_{L,t-1}$):

$$\Pi_t = p_y y_t - w_{L,t-1} L_t - w_{H,t} H_t - c v_t \tag{4.11}$$

where p_y is the price of the two goods, y_t is the output, $w_{L,t-1}L_t$ and $w_{H,t-1}H_t$ are the wage costs for low and high-wage labour, and cv_t is a cost of vacancy posting. Output is produced with the following production technology $F(L, H)$:

$$y_t = F(L, H) = L_t^{\alpha} H_t^{1-\alpha} \tag{4.12}$$

The realised amount of low-wage labour depends on the number of vacancies and the matching probability. All workers are assumed to be unemployed at the beginning of each model round. Low-wage labour in period, L_t, is then defined as:

$$L_t = q(\theta)_t v_t \tag{4.13}$$

where v_t is the number of vacancies posted and $q(\theta)_t$ is the probability of a vacancy to be filled. L_t is currently modelled deterministic, in order to remain as closely as possible to the original model. Low-wage labour thus equals the number of expected matches. When the firm maximises its profit, it is aware of the impact its vacancy postings have on the low-wage labour market and the matching probability, which is defined as:

$$q(\theta)_t = \Omega \left(\frac{N_L}{v_t}\right)^{\xi} \tag{4.14}$$

with Ω and $\xi\ \epsilon(0, 1)$. N_L is the number of low-wage workers and v_t is the number of vacancy postings. From the first order conditions of the profit maximisation, the firm derives the optimal number of low-wage vacancies to post (v^{opt}) and the optimal demand for high-wage labour (H_t^{opt})[7]:

$$v_t^{opt} = \left[\left((p_y \Omega^{\alpha} N_L^{\xi\alpha})^{(1/\alpha)} \alpha(1-\xi) \left(\frac{1-\alpha}{w_{H,t}}\right)^{\left(\frac{1-\alpha}{\alpha}\right)} - w_{L,t-1}\Omega N_L^{\xi}(1-\xi)\right) \frac{1}{c}\right]^{\frac{1}{\xi}} \tag{4.15}$$

$$H_t^{opt} = \left(\frac{p_y(1-\alpha)\Omega^{\alpha} N_L^{\xi\alpha}}{w_{H,t}}\right)^{\frac{1}{\alpha}} v_t^{opt(1-\xi)} \tag{4.16}$$

[7]See also Appendix 4.B.

3. *Labour supply*

   High-wage households determine their optimal labour supply given the consumption price level, tax rates and the wage rate offered by the firm. The consumption price level is defined as:

$$p_{g,t} = \frac{p_y S_{C,t-1} + (1+\tau_{D,t}) p_y S_{D,t-1}}{S_{C,t-1} + S_{D,t-1}} \tag{4.17}$$

   where $S_{C,t-1}$ and $S_{D,t-1}$ denote the amount of goods C and D sold in the previous period.

   The labour supply curve is the result of the maximisation of high-wage households' utility, which is defined as:

$$Q_{i,t} = (C_{i,t})^{1-\sigma}(D_{i,t} - \bar{D})^{\sigma} \tag{4.18}$$

   This is the same equation as in A&CA (Eq.(1)). In addition, households take into account their income constraint and the effort cost function from Eq.(4.1). Individual labour supply is thus defined as:

$$h^S = \left[\frac{(1-\tau_{H,t})w_{H,t}}{p_{g,t}}\right]^{\eta_H} \tag{4.19}$$

   where $p_{g,t}$ is the consumption price level, $w_{H,t}$ is the high-wage rate and $\tau_{H,t}$ is the income tax rate for high-wage labour. Total high-wage labour supply is $H^S = \sum_1^{N_H} h^S$. As mentioned earlier, η_H can be interpreted as the Frisch elasticity of labour supply to the wage. This functional form implies that high-wage households will react to a price increase by lowering their labour supply.

4. *High-wage labour market*

   If high-wage labour supply exceeds demand, work is distributed equally among all high-wage applicants. If labour demand exceeds supply, the firm hires as much high-wage labour as possible, in which case the households meet their optimal labour supply target.

5. *Low-wage labour market*

   Independently of the outcome in the high-wage labour market, the first $v_t q(\theta)_t$ low-wage workers are matched with the open vacancies. The new low-wage rate is the outcome of a negotiation between the firm and its workers, who split the job rent according to the bargaining power of workers (β). The reservation wage of the low-wage workers is defined as:

$$w_{R,t} = \frac{B_t + p_{g,t} Z}{1 - \tau_{L,t}} \tag{4.20}$$

   It depends on unemployment benefits, B_t, the utiliy from leisure, valued at the overall price level of consumption ($p_{g,t} Z$), and the low-wage income tax rate $\tau_{L,t}$. At a low-wage rate $w_{R,t}$, a worker is indifferent between being employed or unemployed. The optimal low-wage rate is:

$$w^*_{L,t} = w_{R,t} + \beta \left(\frac{\partial y}{\partial L_t} - w_{R,t} \right) \tag{4.21}$$

In this case low-wage workers and firm meet between the reservation wage $w_{R,t}$ and the marginal product of a unit of low-wage labour $\frac{\partial y}{\partial L_t}$, i.e. the difference in profit for the firm when the job is created versus keeping it unfilled. In the ABM, the actual wage rate is always moving from the wage in the previous round $w_{L,t-1}$ towards its optimum $w^*_{L,t}$ by $X\%$. The low-wage rate is thus defined as:

$$w_{L,t} = \begin{cases} (1+X)w^*_{L,t-1} & \text{if } w^*_{L,t} > w_{L,t-1} \\ (1-X)w^*_{L,t-1} & \text{if } w^*_{L,t} < w_{L,t-1}. \end{cases} \tag{4.22}$$

6. *Consumption planning*

All households are now aware of their income in period t and make an optimal consumption plan. The determination of optimal consumption of goods C and D is the same for low- and high-wage households. Consumption utility depends on a necessary level of polluting subsistence consumption ($\bar{D}$) and follows from the maximisation of Equation (4.18) subject to an income constraint $I_{i,t} + Div^{cv}_t + Div^{\pi}_t = p_y C_t + (1+\tau_{D,t})p_y D_t$. $I_{i,t}$ is the income from labour or benefits. Div^{π}_t and Div^{cv}_t are dividends from profit and vacancy costs paid to each household equally.

$$I_{i,t} = \begin{cases} (1-\tau_{H,t})w_{H,t-1}h_{i,t} & \text{for high-wage HHs,} \\ (1-\tau_{L,t})w_{L,t-1} & \text{for employed low-wage HHs,} \\ B_t & \text{for unemployed low-wage HHs.} \end{cases} \tag{4.23}$$

Maximising the utility function with respect to these constraints yields the following optimal demand for C and D[8]:

$$C^*_t = \frac{1-\sigma}{p_y} * \left(I_t - \frac{(1+\tau_{D,t})p_y}{p_y} \bar{D} \right) \tag{4.24}$$

$$D^*_t = \frac{\sigma}{(1+\tau_{D,t})p_y} * I_t + (1-\sigma)\bar{D} \tag{4.25}$$

7. *Production process*

The firm is facing (private) demand from the households. Additionally, we follow the GEM in that a positive government balance is spent on a clean public good (G). This positive balance occurs when income and pollution tax revenues exceed unemployment benefits. Hence, revenues in each period (divided by the price for C) are added to the demand for the firm's

[8] See Appendix 4.C for optimal demand in the GEM.

clean good. Total demand for C is then:

$$C_t^D = \begin{cases} \sum_{N_L+N_H} C_{i,t}^* + \left[\frac{GR_t}{p_y}\right] & \text{if GR} \geqslant 0, \\ \sum_{N_L+N_H} C_{i,t}^* & \text{otherwise.} \end{cases} \tag{4.26}$$

where $C_{i,t}^*$ is household i's optimal demand for good C from equation (19) and GR_t is the approximated government revenue in the current period.

Private demand for the polluting good (D) is:

$$D_t^D = \sum_{N_L+N_H} D_t^* \tag{4.27}$$

C_t^D and D_t^D denote overall demand and N_L and N_H is the number of low- and high-wage workers. The firm produces as much as it can with the given labour inputs. Production is assigned to C and D according to the share of total demand for these goods observed among the households and the public sector. Supply of C and D are thus defined as:

$$C_t^S = (1 - R_t)y_t \tag{4.28}$$

$$D_t^S = R_t y_t \tag{4.29}$$

where C_t^S and D_t^S is the total supply of goods C and D and R_t is the share of D in total demand, calculated as follows.

$$R_t = \frac{D_t^D}{D_t^D + C_t^D} \tag{4.30}$$

8. *Market exchange of goods*

   Goods are sold to households. In case of excess supply, each household can buy their optimal amount. If demand exceeds supply, goods are rationed proportionately. In this case public consumption of C is secured first, before the remaining supply of C can be consumed privately by households. Sales of good j ($j = C, D$) are limited by demand (j_t^D) or supply (j_t^S), depending on which one is lower:

$$S_t^j = \begin{cases} j_t^D & \text{if } j_t^S >= j_t^D \\ j_t^S & \text{otherwise.} \end{cases} \tag{4.31}$$

We calibrate the baseline scenario of the model to an unemployment rate of around 10%, as in the original article's simulations, using Ω and c. All experiments comprise 1000 model rounds. In the cases where a pollution tax is introduced, the implementation happens in period 500. As the empirically grounded ratio of high-wage to low-wage workers used for simulations in the GE study is 46:100, we mimic this proportion when populating the ABM with 460 high-wage and 1000 low-wage workers. We follow the parameter values used by A&CA in their simulations whenever possible. These were chosen to represent the French context. All main parameters are summarized in Table 4.2.

Table 4.2: Model parameters

	Symbol	Description	Value	As in A&CA
Fixed	ξ	Elasticity of matching function	0.5	yes
	p_y	Price of both goods	1	yes
	X	Wage adjustment rate	0.01	no
	ρ	Replacement rate	0.35	yes
	N_H	Number of high-income workers	460	no
	N_L	Number of low-income workers	1000	no
	σ	Share of polluting good in consumption	0.35	yes
	c	Vacancy cost	0.0396	no
	ω	Matching parameter	0.9	no
	α	Production coefficient of low-wage labour	0.41	yes
Scenario-dependent	γ	Redistribution parameter	0	yes
	β	Bargaining power of low-income workers	0.5	yes
	Z	Value of leisure	0	yes
	η_H	Elasticity of high-income labour supply	0.5	yes

Note: Scenario-dependent parameters vary with policy scenarios. Displayed here are baseline values.

We run simulations based on six different propositions. For each proposition we compare the policy scenario with a no-policy scenario, i.e. a perfect counterfactual scenario to the tax reform. As in A&CA the first three propositions refer to an uncompensated pollution tax scenario. In this case pollution tax revenues are treated as savings, which are added to overall government revenue, rather than resulting in any additional public spending. As the original model is static, no further assumptions are made about potential accumulation. In this case the government budget does not have to be balanced, so this is in fact a partial equilibrium situation. Under a compensated tax reform the government budget constraint has to hold, and so the model is closed. This is the case for Propositions 4 to 6. Under a compensated tax reform pollution tax revenues are used to reduce income taxes. Table 4.3 provides an overview of the different scenarios and the respective key parameters.

In contrast to the GEM, the ABM does not focus on marginal changes, but it simulates the economy with different parameter values. Proposition 1 looks at the effects of an uncompensated tax reform at different levels of leisure (Z). Propositions 2, 3, 4 and 5 investigate situations with varying reactions of low- and high-wage labour to the tax (η_H), variation in low-wage workers bargaining power (β) and subsistence consumption ($\bar{D}$). Proposition 6 focuses on the possibility to combine a double dividend (increase in welfare and environmental quality) with a redistributive goal.

Table 4.3: Simulated scenarios

Policy type	Proposition	Scenario controls
Uncompensated tax reform	1	vary Z
	2	$\beta = \xi$, $\eta_H = 0.63$, $\bar{D} = 0$
	3	β, η_H and $\bar{D}$ varied
Compensated tax reform, revenues used to cut income taxes	4	$\beta = \xi$, $\bar{D} = 0$, η_H varies with τ_D
	5	Under double dividend condition, vary β, η_H and $\bar{D}$
	6	vary η_H and γ

The model is coded in Python, using the AgentPy framework (Version 0.1.5) by Foramitti (2021). The data analysis for the proposition tables is performed using R (Version 4.1.0). A repository with the complete source code can be accessed here.[9]

4.3 Results

This section presents the results of the ABM simulations structured according to the propositions of Aubert and Chiroleu-Assouline (2019). Section 4.3.1 addresses the first three propositions under an uncompensated tax reform. Section 4.3.2 treats Propositions 4-6 under a compensated tax reform.

4.3.1 Uncompensated raise in green taxes (Propositions 1-3)

This section presents simulation results related to the first three propositions of the original study. As described above, it is initially a partial equilibrium situation in the sense that pollution tax revenues are not used. A&CA set the pollution tax rate to 1% of the price in their simulations. However, some of their propositions refer to marginal changes in tax rates, in which cases we consider a lower tax rate of 0.01%. While this is obviously still not infinitesimally small, it is closer to the original assumptions. Each model run simulates 1000 periods, where the tax is implemented at the start of period 500. We then run the same scenario without any tax introduction and compare the means of the relevant outcome variables betwen the policy and the no-policy scenario. Each proposition is briefly recapped along with the simulation results.

Proposition 1

The partial equilibrium results comprise a *price effect* and a *substitution effect* on labour. The pollution tax is driving up wages through a higher price of consumption (*price effect*). The *substitution effect* refers to the replacement of one labour type with the other, if their reaction to

[9] https://github.com/franzi-1/Agentization_Klein_et_al

the tax increase is different. The *price effect* only exists when leisure adds to utility, because the price enters the household decision through valuation of leisure. Proposition 1 postulates that if utility does not depend on leisure, employment and productivities remain unchanged. If utility depends on leisure, however, a higher environmental tax will lower labour supply among all workers and thus decrease production. The effects on productivity and labour type ratio in this case are ambiguous, because they depend on the reactions of labour supply from both groups to the tax change.

Table 4.4: Results of an uncompensated pollution tax for distinct leisure values

Leisure value (Z)	Low-wage unemployment rate	High-wage labour	Output	Ratio of low- to high-wage labour	Marginal product$_L$	Marginal product$_H$
0	-4.00	0.14	0.51	0.90	-0.53	0.37
0.01	2.22	-0.16	-0.28	0.14	0.17	-0.12
0.1	-0.35	-0.14	-0.14	-0.31	0.20	0.00

Note: 500 period average, difference in no-tax versus tax scenario. All changes given in percentage. $\tau_D = 0.01\%$, $\bar{D} = 0$ and $\eta_H = 0.5$. For further variables see Appendix 4.D.

Table 4.4 shows the results of our simulations for the relevant parameters given three different values of leisure (Z), and effort cost[10]. That way we can test the proposition for different levels of leisure valuation. Note that a higher Z directly increases the leisure value for low-wage households relative to high-wage households. The values displayed in Table 4.4 are percentage differences in means with and without the policy.

We find that Proposition 1 holds for a moderate value of leisure ($Z = 0.01$), but not for a higher one ($Z = 0.1$). In the first case labour inputs of both household types and output fall as stated by Proposition 1. However, the results under a higher value of Z clearly contradict the "unambiguous negative effect" that A&CA find. However, the effects under a high leisure value are very small. Figure 4.3 also highlights this: there is barely any visible change in the tax (grey) versus the no-tax (black) scenario after the policy introduction under a low leisure value.

Proposition 1 also states, that when utilities do not depend on leisure ($Z = 0$), a higher uncompensated pollution tax does not affect employment and productivities. The reason is that in this case, the price of consumption does not affect labour supply and there is no *price effect.* Contrary to that, we observe a relatively strong change in low-wage employment in this case.

As visible from Figure 4.3, the ABM does not reach a static equilibrium state. Rather than converging to an equilibrium, the ABM suggests relatively stable fluctuations of variables around certain values. These fluctuations still cause changes in wage rates and hence some labour substitution. While A&CA find that the *price effect* always exceeds the *substitution effect*, when utility depends on leisure, this is only the case for a relatively high leisure preference among low-wage

[10]Without any preference for leisure, i.e. when $Z = 0$, there is also no effort cost for high-wage households.

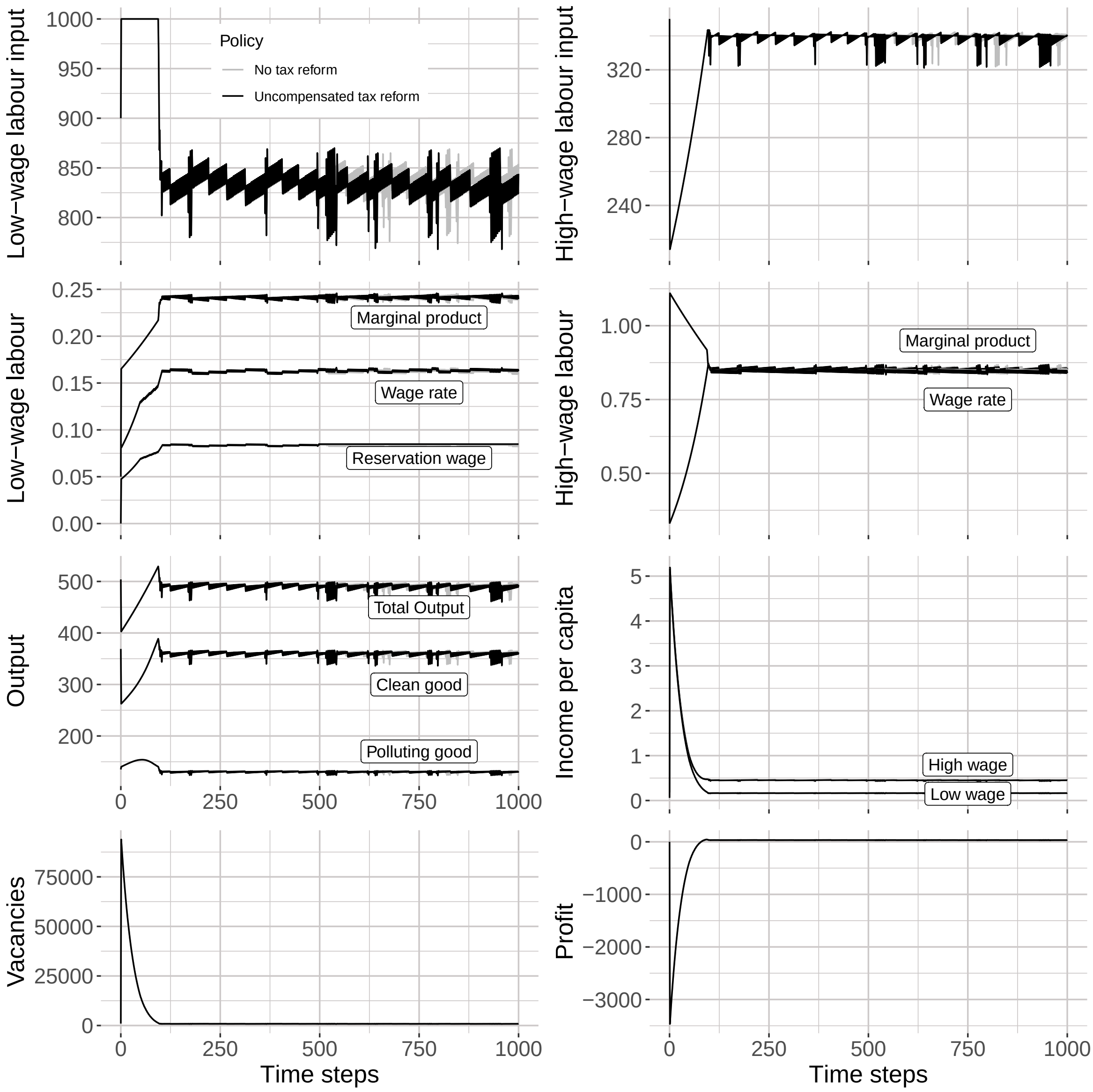


Figure 4.3: Dynamics of main variables without policy and with a 0.01% uncompensated pollution tax, ($Z = 0.01$)

workers in the ABM.

Proposition 2

Proposition 2 concerns the welfare distribution. It states that without any subsistence polluting consumption ($\bar{D} = 0$), but with a balanced low-wage labour market[11] ($\beta = \xi$) and perfect labour substitution[12], the initial distribution will be unaffected by a pollution tax increase. Given the assumption that each household is affected equally by environmental deterioration, the change in

[11] A "balanced labour market" here means that the Hosios condition for constrained efficient markets, in this case a labour market with a search and matching friction, holds. This condition implies that the low-wage worker's share in joint surplus (β) equals the elasticity of the matching function with respect to low-wage workers (ξ) (Hosios, 1990).

[12] "Perfect labour substitution" in the original paper refers to the case when high-wage labour supply elasticity is exactly equal to the reaction of low-wage labour to the outside option. Here we interpret this as a proportionate change in actual labour of both types.

welfare is measured as the difference in average purchasing power (PP) of low- and high-wage households ΔPP_i under a tax reform, compared to no policy:

$$\Delta PP_i = I_{i,1} - I_{i,0} - \tau_D p_y D_{i,0} \tag{4.32}$$

where i indicates the household type, $I_{i,1}$ is the average per capita income of that household type under the tax policy, $I_{i,0}$ is their income without any pollution tax. $\tau_D p_y D_{i,0}$ can be interpreted as the change in the cost of keeping up no-policy consumption of D (*compensating variation*). If the loss (gain) in purchasing power is higher (lower) for low-wage households relative to high-wage households, the policy is called *regressive*. Otherwise it is considered *progressive*.

We set η_H to approach the "perfect substitution" condition. This is a difficult task, as the effect of η_H on labour substitution appears highly non-linear[13]. Under an uncompensated pollution tax of 1%, $\eta_H = 0.63$ is the closest we find to a proportionate labour reduction. This third condition ("perfect labour substitution") should be noted as a general problem for both types of models. From an ABM perspective, it is difficult to define conditions as exact as a GEM. For GEM results, it should be kept in mind that their results often concern highly special cases, which may be unlikely to occur in reality. Table 4.5 shows the distributional effects of the policy with different levels of low-wage workers' bargaining power (β) and the high-wage labour supply elasticity (η_H)[14].

Table 4.5: Distributional impacts of an uncompensated pollution tax for varying labour supply elasticity (η_H) and bargaining power (β), given matching elasticity (ξ)

High-wage labour elasticity (η_H)	$\beta < \xi$	$\beta = \xi$	$\beta > \xi$
0.3	Progressive 0.07	Progressive 0.14	Progressive -4.44
0.5	Progressive 0.11	Regressive 0.12	Regressive 0.17
0.63	Regressive 0.14	Progressive 0.08	Progressive -1.03
0.8	Regressive 0.16	Progressive -0.19	Progressive -1.02

Note: 1000 periods, tax implemented in t=500. $\tau_D = 1\%$. Numbers indicate change in mean labour input ratio (L/H) under a tax policy compared to no policy in percent. Detailed effects on purchasing power in Appendix 4.E.

We predominantly observe progressive policy outcomes. Regressivity appears mainly when labour is shifted towards low-wage households ($\Delta \frac{L}{H} > 0$) and high-wage labour supply elasticity is above a certain level. When the conditions of Proposition 2 are fulfilled ($\eta_H = 0.63$ and $\beta = 0.5$) the policy is progressive. In fact, it is even more progressive than in some of the other cases displayed in Table 4.5 (compare Appendix 4.E). Hence we cannot confirm the proposition, although the changes in purchasing power are very small.

[13]See Appendix 4.F for further information on our approach.
[14]Detailed results in terms of purchasing power in Appendix 4.E.

Proposition 3

Proposition 3 follows from the first two propositions. It claims that the regressivity of an uncompensated tax is stronger when (i) unemployment is above its optimum, (ii) the difference in elasticity of high- and low-wage labour with respect to the green tax or the outside option is larger, or (iii) the level of subsistence consumption is higher. To test this proposition, we run the baseline simulation increasing subsequently the value of β (i.e. underemployment), the value of η_H (i.e. stronger high-wage labour elasticity), and $\bar{D}$ (subsistence consumption of D).

Table 4.6 shows the differences in average purchasing power between a tax and a no-tax scenario for a baseline with $\eta_H = 0.63$ and $\beta = \xi$ (first row) and the three cases suggested above. The results are in line only with the last suggestion of Proposition 3. A positive subsistence level of polluting consumption increases the regressivity of the tax reform. An increase in β, relative to ξ and a higher elasticity of high-wage labour supply (η_H), on the other hand render the initially progressive policy even more progressive.

Table 4.6: Change in purchasing power under an uncompensated tax reform by household type

Scenario	Controls	Change in high-wage purchasing power	Change in low-wage purchasing power
Baseline	$\beta = \xi = 0.5$ $\eta_H = 0.63$ $\bar{D} = 0$	-0.92	-0.81
Underemployment	$\beta = 0.75$	-2.02	-0.39
High elasticity of H	$\eta_H = 0.8$	-1.53	-1.03
High subsistence level	$\bar{D} = 0.1$	-1.69	-4.34

Note: $Z = 0$ in all cases here, $\tau_D = 1\%$. 500 period average of no-tax versus tax scenario. All changes given in percentage.

4.3.2 A revenue-neutral tax reform (Propositions 4-6)

This subsection investigates a revenue-neutral tax reform, i.e. a situation when carbon tax revenues are recycled through cuts in labour taxes, and looks at the conditions for obtaining a double dividend (DD). Propositions 4 and 5 concern a situation where tax cuts are proportionate between the two labour types, whereas Proposition 6 addresses a combination of equity and efficiency concerns by redistributing tax revenues towards low-wage workers. We are focusing mostly on a tax rate of 1%, similar to the simulation part of the original model.[15]

Proposition 4

Given the tax system is Laffer-efficient, under the conditions of Proposition 2 (Hosios condition

[15] As mentioned above, contrary to the GEM, in which government expenditure (G) is fixed, we allow for variation in G to keep the model stock-flow consistent. However, the variation does not come from changes in tax revenue, which we keep constant, but from variations in unemployment and hence benefit payments.

holds, homothetic preferences, perfect labour substitution) any revenue-neutral tax reform with proportionate labour cuts is regressive. The intuition is that uniform cuts in labour tax rates are naturally regressive, because they do not compensate unemployed workers. Under the conditions above, the potentially progressive revenue (or income) effect through changes in productivities and wage rates is always exceeded by the initial regressive nature of uniform tax cuts.

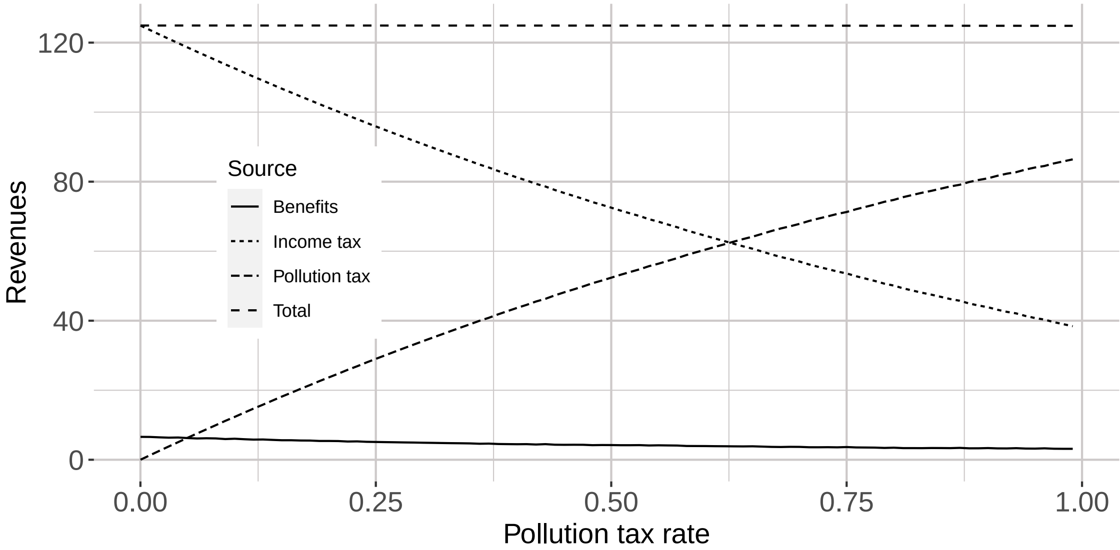


Figure 4.4: Tax revenues and expenditure

The condition of "perfect labour substitution", i.e. no substitution between both labour types, is reached at different levels of η_H when the tax increase is compensated or uncompensated, because the change in net wages is different. So while we previously simulated experiments with $\eta_H = 0.63$ to meet this condition, we are now setting it to 0.61 under a compensated tax reform. To test this proposition, we further need to check if the tax system is Laffer-efficient, i.e. if an incremental tax rate increase leads to an increase in tax revenues. For our model setup, when pollution tax revenues are recycled to households through income tax cuts, revenues always increase with the pollution tax rate for any reasonable value of τ_D. Figure 4.4 shows tax revenues, broken down by income source for pollution tax rates between 0.01% and 100%.

Table 4.7 shows the changes in purchasing power for high- and low-wage households for a range of pollution tax rates. In order to meet the condition that no labour substitution should be taking place, η_H needs to be varied.[16] We observe a regressive policy outcome in every case, typically with an increase in purchasing power for high-wage households and a decrease for low-wage households, with the exception of a very low tax rate of 0.01%. The regressivity further increases with a higher pollution tax rate. Based on these results, Proposition 4 can be confirmed, because the small changes in purchasing power under the lowest tax rate (0.03%) are within the margin of error. As

[16] Appendix 4.F displays the relationship between η_H and the ratio between the two labour inputs for different pollution tax levels.

Table 4.7: Change in purchasing power under a compensated tax reform for different pollution tax rates

Scenario	Controls	Change in high-wage purchasing power	Change in low-wage purchasing power
Baseline	$\beta = \xi = 0.5$, $Z = 0$, $\eta_H = 0.61$, $\bar{D} = 0$, $\tau_D = 1\%$	0.61	-0.15
Proposition 4	$\tau_D = 0.01\%$, $\eta_H = 0.44$	-0.03	0.03
	$\tau_D = 5\%$, $\eta_H = 0.51$	2.62	-0.56
	$\tau_D = 10\%$, $\eta_H = 0.39$	4.35	-1.66
	$\tau_D = 50\%$, $\eta_H = 0.33$	10.33	-12.96
	$\tau_D = 100\%$, $\eta_H = 0.33$	6.91	-31.37

Note: 500 period average of no-tax versus various tax scenarios. All differences given in percentage. η_H needs to be varied to meet the perfect substitution condition (see Appendix 4.F).

suggested, the revenue-neutral tax reform turns out to be clearly regressive for most of the tax rate levels considered here.

The double dividend conditions

Goulder's *strong double dividend* claims that an ETR can have welfare increases beyond environmental improvement (Goulder, 1995). When the tax reform is revenue-neutral, i.e. the government budget is balanced through income tax reductions, the *environmental dividend* requires that the total consumption of D decreases. The *welfare dividend* requires an increase in purchasing power, i.e. that the increase in wages and employment[17] (i.e. incomes) exceeds the welfare reduction through lower consumption of D.

If the tax adjustment is proportionate, $d\tau_H = d\tau_L = d\tau$, the double dividend can be achieved if and only if the variation in total polluting consumption plus any disutility from work is lower than the variation of total household income, which in turn is lower than the variation of real income from the pollution tax. In other words, the income gains from the reform have to be high enough to compensate for utility losses, but not too high, in order to allow for decreasing consumption of D.

Proposition 5

If a tax reform fulfills the conditions for a double dividend, it tends to be more progressive if unemployment is above the "optimal" level (i.e. $\beta > \xi$), there is a stronger substitution effect between labour types, and if subsistence levels of consumption are lower.

Under a 1% pollution tax rate, the double dividend conditions are fulfilled: Consumption of D drops and purchasing power increases for both household types. Figure 4.5 shows that sales of the polluting good D drop (environmental dividend) under the tax reform (solid line) compared to a no-tax scenario (dashed line). At the same time, the policy increases overall purchasing power (economic dividend). It should be noted that the effects are relatively small compared to the

[17] And in this case the changes in dividends

fluctuations of the model.

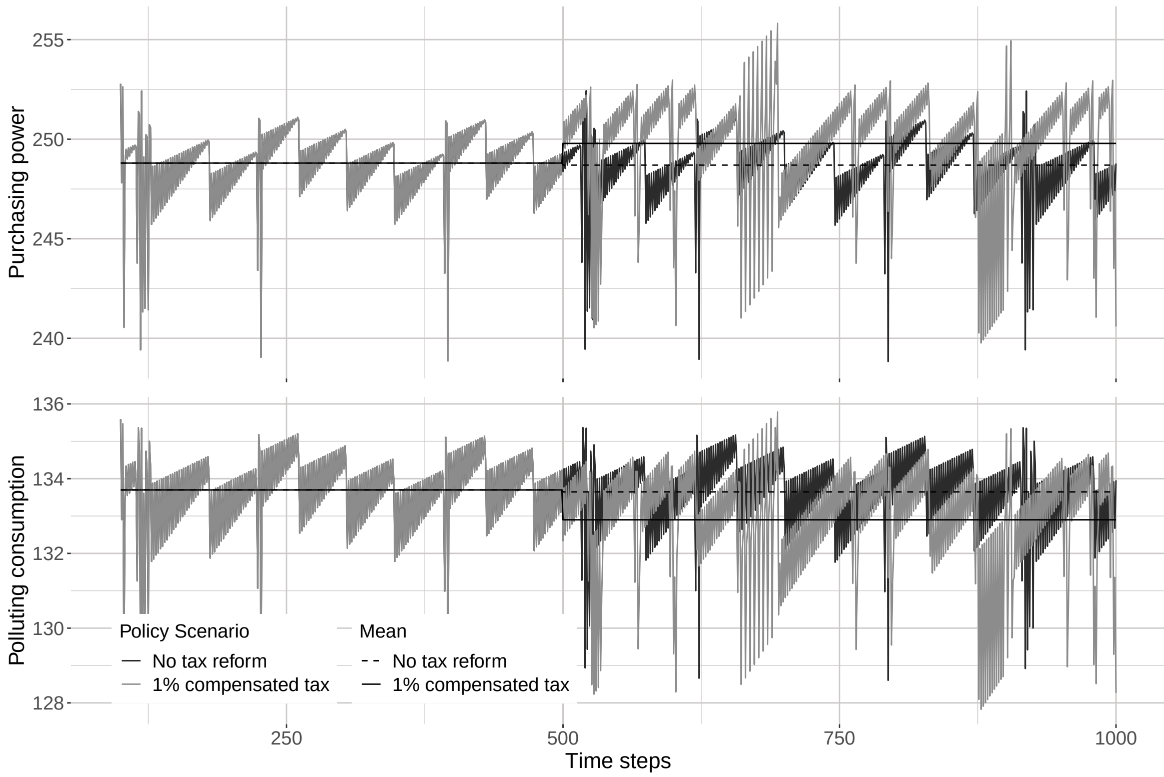


Figure 4.5: Double dividend of a compensated tax reform ($\tau_D = 1\%$)

Note: The solid line represents average value under the tax reform, the dashed line the no-tax scenario.

The results in Table 4.8 partly confirm the proposition. A larger difference in the reaction of high-wage labour supply and low-wage employment ($\eta_H = 0.8$) and a lower subsistence level of polluting consumption reduce the regressivity of the tax reform. Higher low-wage bargaining power, however, leads to a more regressive outcome here.

Proposition 6

Proposition 6 states that under (above) a certain threshold of the Frisch elasticity of high-wage labour supply (η_H), it is always (never) efficient to redistribute revenues from a tax reform progressively. The basic idea here is to combine the double dividend with equity considerations (a "third" dividend).

Table 4.9 presents three levels of a Frisch high-wage labour elasticity each combined with three levels of the *progressivity index* γ. The two lower values for γ lie within the range suggested in the original paper. Additionally, we include an extreme redistribution value of $\gamma = 0.99$, where pollution tax revenues are almost entirely recycled through tax cuts for low-wage workers (99%).

As we can see from the change rates of purchasing power by household type, all scenarios are progressive and thus meeting our equity criterion. The environmental dividend is also reached

Table 4.8: Change in purchasing power under a compensated tax reform

Scenario	Controls	Change in high-wage purchasing power	Change in low-wage purchasing power	Ratio of low- to high-wage labour
Baseline	$\beta = \xi = 0.5$ $Z = 0$, $\eta_H = 0.5$ $\bar{D} = 0$	0.39	-0.19	0.06
Proposition 5	$\beta = 0.75$	2.21	-0.12	1.87
	$\eta_H = 0.8$	-1.67	-1.11	-0.21
	$\bar{D} = 0.1$	1.95	-0.46	0.07

Note: 500 period average of no-tax versus various tax scenarios. $\tau_D = 1\%$. All changes given in percentage.

across all cases and the reduction in polluting consumption appears to be increasing with η_H. Total purchasing power, on the other hand, is increasing only under a lower high-wage labour elasticity. The welfare dividend is thus prevented under a high η_H. Our results thus support the proposition. However, in those cases where the welfare gain is larger, the reduction in polluting consumption is smaller. Thus, in the ABM, there seems to be not so much a trade-off between equity and efficiency, but rather between the two dividends. Combining equity with efficiency would be easier when η_H is neither too high, nor too low. It should be noted again that the ABM generates overall more progressive results, because profits and vacancy costs are recycled to all households. Both wage incomes and dividends are higher when η_H is lower, although wages make up the bulk of household income (see Figure 4.6

Table 4.9: Change in purchasing power and polluting consumption under a compensated tax reform with redistribution

High-wage labour supply elasticity, η_H	Redistribution parameter, γ	High-wage purchasing power	Low-wage purchasing power	Overall purchasing power	Polluting consumption
0.1	0.45	-6.71	8.79	3.91	-0.72
	0.55	-8.05	11.23	5.16	-0.55
	0.99	-16.52	22.32	10.08	-0.73
0.5	0.45	-9.28	6.66	1.64	-2.18
	0.55	-12.04	8.20	1.82	-2.76
	0.99	-25.66	15.58	2.58	-5.68
0.8	0.45	-15.18	3.42	-2.44	-5.19
	0.55	-18.46	4.62	-2.65	-6.04
	0.99	-41.01	6.96	-8.15	-13.61

Note: 500 period difference in average no-tax versus compensated tax scenarios in percentage.

Table 4.10 briefly summarises the key insights regarding each of the six propositions and if they confirm the original statements. The replication success is somewhat mixed. We find partial evidence for Proposition 1: Employment for both labour types and overall production levels decline, but only when the leisure value is neither too high, nor too low. Contrary to the proposition we observe changes in labour inputs triggered by a pollution tax, even when leisure is not valued. Similarly, the ABM results oppose Proposition 2, which states that under optimal low-wage employment, when there is neither labour substitution, nor subsistence consumption, a pollution tax

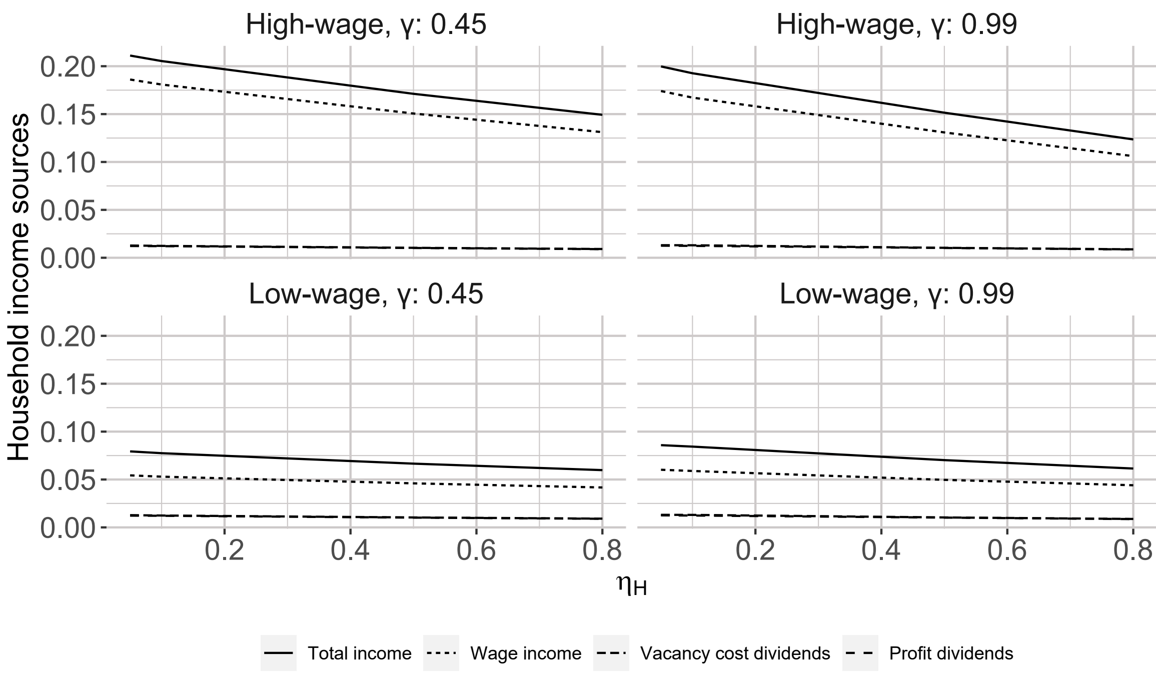


Figure 4.6: Income at different levels of η_H and γ by source and household type

does not have any redistributive effect. In our model the uncompensated tax is progressive in this case. However, the effects on purchasing power are very small and fall in the margin of error. Proposition 3 can be confirmed with respect to subsistence consumption. Similarly, Proposition 5 holds only concerning subsistence consumption and the effect of labour supply elasticity. The effect of a higher bargaining power works in the opposite direction than suggested by Propositions 3 and 5. Proposition 4 holds for all tax rates except the smallest, and can be considered confirmed. Proposition 6 is also supported by our results.

4.3.3 Sensitivity analysis

To test the robustness of the results, we perform sensitivity analyses with respect to changes in the pollution tax rate τ_D, the value of leisure Z, the high-wage labour supply elasticity η_H, low-wage workers' bargaining power β, the subsistence level of polluting consumption $\bar{D}$, and the redistribution parameter γ. As many variables show considerable fluctuations, rather than convergence to one value, we test the impact of an earlier (or later) policy implementation as well.

Our agent-based approach is ideally suited for the analysis of probabilistic dynamics, so we also tested whether a probabilistic search-and-matching process changes the results, compared to a deterministic setting. In addition, we performed simulations with different initial values for key variables, such as the wage rates, levels of output, demand and income. However, we find that these changes only affect the duration of the burn-in period, but not the quality of the results.

We also ran the experiments with a lower consumption price level, including the adjustment of

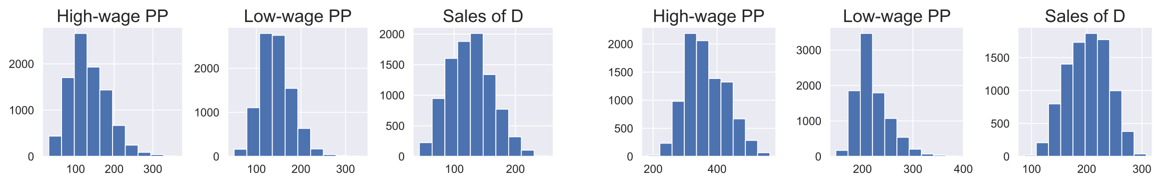
Table 4.10: Key results of the ABM by proposition

Tax	Prop	Key result	Confirms A&CA
Uncompensated	1	The proposition holds for a moderate leisure value. Otherwise employment increases for low-wage workers.	Partly
	2	Under the given conditions, the policy tends to be slightly progressive, rather than neutral.	Unclear
	3	The policy is more regressive only when the level of subsistence consumption is higher. Contrary to the proposition, when unemployment is above its optimum, or the difference in the reaction of high- and low-wage labour to the tax is stronger, the policy is more progressive.	Partly
Compensated	4	A revenue-neutral tax reform with uniform revenue recycling is regressive for all tax levels except the lowest one (0.001%).	Yes
	5	The policy becomes less regressive only when the level of subsistence consumption is lowered. Contrary to the proposition, when unemployment is above its optimum, or the difference in the reaction of high- and low-wage labour to the tax increases, it becomes more regressive.	Partly
	6	Under (above) a certain threshold f η_H it is always (never) efficient to redistribute tax revenues progressively.	Yes

the vacancy cost, c and η_H to meet the "perfect substitution" condition. In this case Proposition 1 holds only under the higher level of Z (0.1). The lower price level also seems more conducive to the propositions related to the Hosios condition. According to this condition, a market is constraint efficient if the workers' surplus share (β) equals the sum of the matching elasticity (ξ) and the surplus elasticity. The latter is the effect of job creation on profits, or the job rent. We suspect that under our price level of 1, the surplus elasticity effect is larger, so the Hosios condition is met at a higher level of β. While the GEM assumes a zero-profit equilibrium situation, the impact of job creation on profits can be neglected. In the ABM, however, the job rent is affected by the price level and the Hosios condition is unlikely to hold at the original condition in A&CA: $\beta = \xi$. This may explain why parts of Proposition 3 and 5 do not hold. Both, the Hosios and the "perfect substitution" condition describe very specific cases, which turn out difficult to replicate with an ABM.

For the variables mentioned above, we are performing a Sobol sensitivity analysis using two Saltelli samples of different parameter combinations, one for an uncompensated and one for a compensated tax reform (see Saltelli, 2002 and Sobol, 2001 for further background on this method). The former includes changes in high-wage workers' effort cost, the latter variation in the progressivity index. The sample size amounts to 9216 model runs in each case. The effects on the main variables of interest in this paper, sales of the polluting good and total real household income after subsistence consumption (PP) are presented in Figures 4.7 to 4.9.

Figure 4.7 plots the distribution of several model outcomes for the samples of the two reform types. The distribution of purchasing power and sales of the polluting good are similar under both policies. They are all slightly right-skewed, indicating few scenarios with high purchasing power or polluting consumption.



(a) Uncompensated tax reform

(b) Compensated tax reform

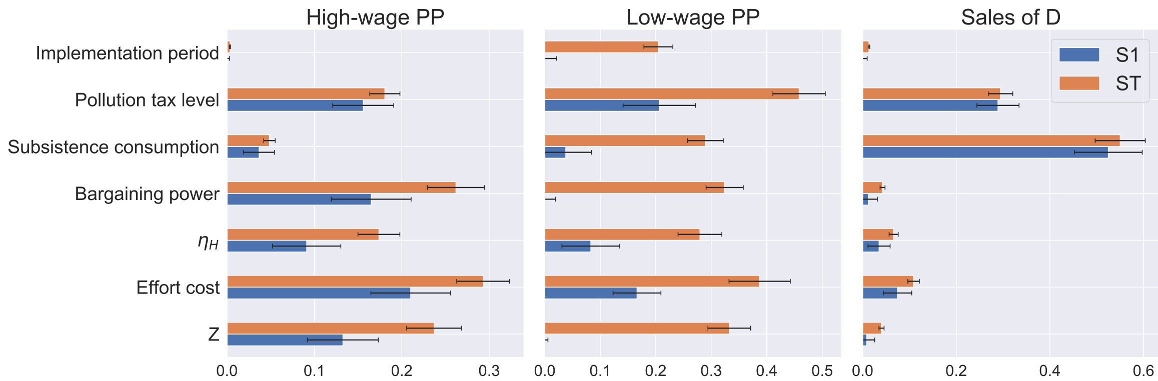
Figure 4.7: Histograms of outcome variables (each N=9216)

Figure 4.8 shows the first (S1) and total order (ST) Sobol sensitivity indices, as well as their confidence ranges. S1 measures the contribution of a parameter to the respective model outcome alone. ST includes second-order effects through interactions in the model. The level of low-wage purchasing power is particularly dependent on the parameters tested here. This holds for both policy types and is in line with the strong fluctuations our model shows for the low-wage labour market. Secondary effects arise in particular through the pollution tax and effort cost of high-wage households when revenues are not recycled. Under a compensated tax reform, bargaining power of low-wage workers becomes more important relative to the other parameters tested.

High-wage purchasing power proves to be more robust to the parameters tested when tax revenues are recycled. In that case leisure preference and bargaining power of low-wage workers are the most important determinants, whereas the level of the pollution tax and their own reaction to the policy play a considerably more important role in an uncompensated tax reform. Overall, higher-order effects play a relatively more important role for high-wage PP than for low-wage PP. The latter is effected directly by basically all parameters. Perhaps not surprisingly, the strongest effects for polluting consumption can be seen for the tax stringency and the subsistence level, both of which show considerable total order effects as well.

Finally, to understand the direction of the impacts, we plot our outcome variables for each parameter's value range in Figure 4.9. Here it should be noted that the emerging patterns are quite similar for most relationships independent of the policy type. Higher low-wage leisure value and bargaining power both lower high-wage PP and consumption of D and are related to low-wage PP in a U-shaped manner. A higher elasticity of high-wage labour supply (η_H) goes with a reduction in all three outcome variables. So does a higher subsistence level of D, with the exception of high-wage PP in a compensated tax reform. This actually increases in $\bar{D}$. The implementation period does not seem to have a notable impact on either purchasing power, or pollution consumption.

Opposite to what we would expect, high-wage PP (low-wage PP) seems to be increasing (decreasing) in the redistribution parameter γ. Tis is due to the range of pollution tax rates we test. When pollution tax revenues are high, balancing the government budget requires to go beyond lowering the income tax rates and actually leads to labour subsidies, or negative income tax rates.



(a) Uncompensated tax reform

(b) Compensated tax reform

Figure 4.8: Sobol sensitivity indices

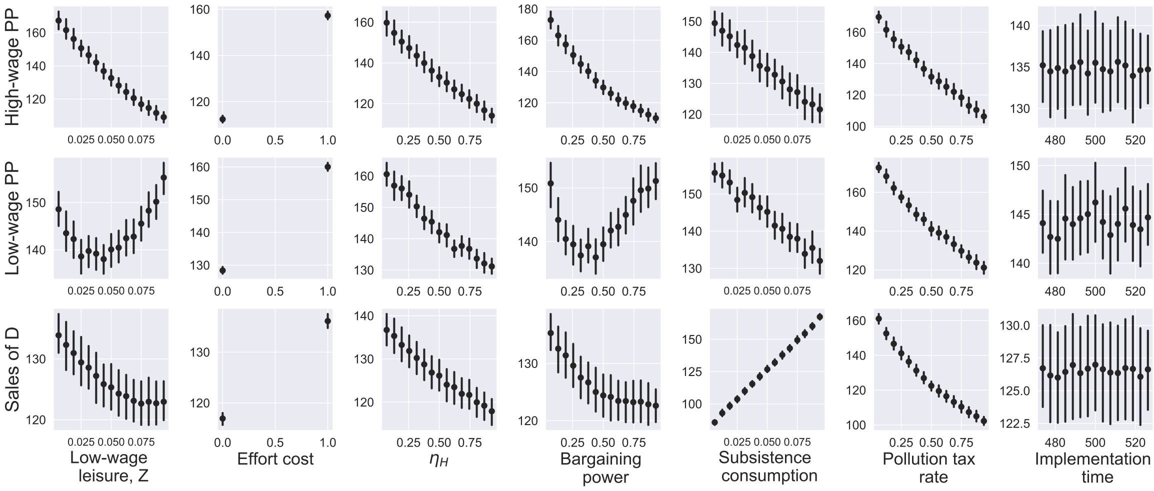
The way that γ is set up, it lowers the ratio of low- to high-wage income tax rates. Under a positive tax rate this leads to redistribution towards low-wage workers. Under negative tax rates, however, tax incidence shifts towards low-wage workers, redistributing towards high-wage earners. Thus, the proposed redistribution parameter only works as intended in the case of a positive income tax, i.e. under relatively low pollution tax revenues. To avoid increasing inequalities, one would have to adjust the current rule for income tax setting, or otherwise either abandon the assumption of subsistence consumption or limit the analysis to low pollution tax rates.

4.4 Agentization Challenges

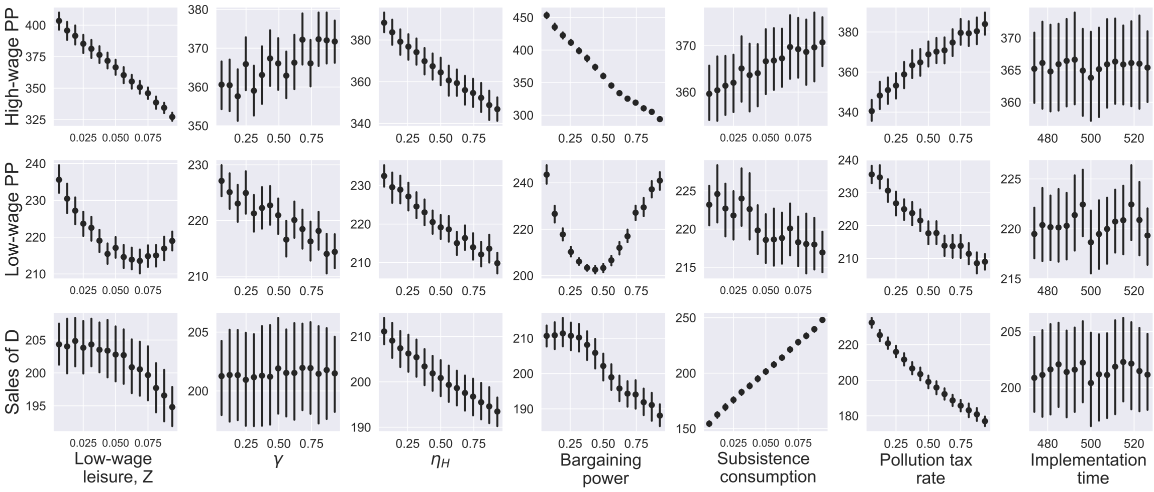
This section outlines some of the challenges that we encountered during the agentization process.

Equilibrium

We faced several methodological challenges when translating the general equilibrium model into an agent-based model. The first issue concerns one of the core assumptions of GEMs: the existence of an equilibrium. The original article investigated marginal effects of a tax reform starting from a hypothetical equilibrium without knowing or determining its levels. Simulating an ABM involves



(a) Uncompensated tax reform



(b) Compensated tax reform

Figure 4.9: Sensitivity of purchasing power and polluting consumption (y-axes) to a number of parameter value ranges (x-axes)

determining an equilibrium levels. Hence the first challenge was to find an approximation of an equilibrium. Testing many different parameter combinations, we could not establish a convergence to any stable equilibrium. The variables in the ABM move towards a pseudo-equilibrium around which they fluctuate. These fluctuations arise because of the dynamic elements of the ABM, where actions happen in sequence, and certain variables (e.g. the wage rates) adjust gradually over time. If lagged variables create a cycle of opposite movements, the model cannot converge to a stable equilibrium. To test the propositions we worked around this issue by comparing average values of the variables of interest with and without a policy. However, this is generally affecting our outcomes, especially regarding Propositions 3 and 5. It should be noted also that some of the observed policy effects are negligible in size compared to the model fluctuations (see e.g. Figure 4.5).

Sequence and order of actions

A key difference between ABMs and especially static equilibrium models is the relevance of transitions. While equations are solved simultaneously in GEMs, the ABM needs to assume an order, a sequence of events and decisions, which is not always clear from mainstream economic theory. We have explained our approach in detail in Section 4.2.2. One example is that households reconsider their optimal consumption after knowing their income in a respective period. At other times, we tried to overcome problems with sequenced actions. For instance, the firm is hyper-rational with respect to the impact of its vacancy posting on the low-wage labour market. On the other hand, the firm uses lagged variables of low-wage rates when forming its profit expectations. There is a constant conflict between applying lagged knowledge or perfect foresight when dealing with sequential behaviours.

Theoretical consistency

General equilibrium models have been developed alongside neoclassical economic theory and thus provide a good representation thereof. The fundamentally different nature of ABMs, for instance in terms of sequence or disequilibrium states, also highlights the different fundamental understanding of economic systems as complex and evolving over time. For us, this became especially clear in the decision between above-mentioned lagged (and thus imperfect information) and hyper-rational perfect expectations, which finally depends on underlying theoretical understandings. The take-away message is that agentizing a GE model naturally leads to a confrontation with the theoretical framework. The difficulty lies in solving practical coding problems while keeping theoretical consistency. Therefore, we recommend careful consideration of the underlying assumptions linked to pragmatic coding decisions.

Stock-flow consistency

Another issue linked to consistency concerns the accounting of stocks and flows in the model. The transition towards an equilibrium requires assumptions about monetary flows, which are irrelevant in the equilibrium state itself. Any profits, for example, have to be attributed to some purpose or agent. The resulting income distribution will be distinct, depending on whether we pay profits as a dividend to everyone or to, say, just a small number of capital owners.

A less trivial example of a SFC problem is the cost of posting vacancies. It is unclear how to interpret this flow. In the GEM this cost is balanced through the job rent leading to a zero profit expectation. In the ABM, this search friction in the low-wage labour market leads to a constant generation of positive profits for the firm. Evidently, this money cannot simply vanish. It may be interpreted as a fee being paid to some job placement database or agency that connects workers with the firm. Our interpretation here is that the money cannot leave the economy and hence we channel it back as a per capita dividend to all households which translates into higher demand.

Another example where additional assumptions were needed for SFC is the provision of the clean public good (G). While G is assumed to be exogenously fixed, as in the GEM, government revenue changes from one time step to the next, so that the desired level of public goods may not be affordable any longer in the ABM. In that case it needs to be decided how to treat changes in revenues. It also has to be clear whether the clean public good stems from the production of the representative firm. We assumed that it does and hence has added it to overall demand for C. These are important issues. In our particular example, the dividends from profits and vacancy costs give our economy a more Egalitarian character and can render policy outcomes slightly more progressive.

Upscaling

Scaling up a model from single representative to multiple agents is an essential characteristic of agentization. In this study, the number of agents was an almost purely technical exercise because we kept each group of agents very homogeneous. Thus they compare well to the GEM's representative agents. However, under different circumstances, for instance non-constant returns to scale of the production function, the number of agents greatly affects the model outcome and may require an adjustment of other parameters. In our model scaling up the number of agents mostly affects the treatment of probabilistic actions. Equations related to the search and matching process, in this study in particular the matching function, have to be adjusted to the number of household agents in the model. We tested the model through replacing the deterministic by a stochastic matching process in the low-skilled labour market, i.e. a random matching process where against the odds the firm could end up with too few or too many workers, and also with a deterministic process, i.e. the expected number of matches was calculated based on vacancies posted and matching probability and then this exact number of matches was enforced. In our case this choice did not have a relevant impact on the results, because there is no notable heterogeneity within our two groups of agents.

4.5 Conclusions

Effective climate policies are likely to induce fundamental changes in our economies and thereby lead to considerable out-of-equilibrium dynamics. To promote a broader methodological approach to studying such policies, and environmental tax reforms in particular, this study replicated a general equilibrium model of a tax reform using an agent-based approach. We therefore built a basic ABM, remaining as closely as possible to the original GE model's features and assumptions. This contributes to the literature by (i) providing a starting point for linking more elaborate agent-based analyses of environmental tax reforms to the GEM literature, (ii) facilitating a direct methodological comparison between a GEM and an ABM approach, and (iii) allowing to test the replicability of the original model's results.

The ABM supports most of the propositions made based on the GE model at least in part. Similarly to Aubert and Chiroleu-Assouline (2019), we find that the pollution tax is basically always regressive, if its revenues are given back to workers proportionately. In a situation with homothetic preferences and no labour substitution an uncompensated tax is close to neutral when the Hosios condition of a constrained efficient labour market holds, i.e. the workers' surplus share equals the matching elasticity. However, the ABM shows a slightly progressive tendency here. One reason may be the difficulty of replicating the exact conditions.

In the ABM as in the GEM, the existence of subsistence polluting consumption, implying non-homothetic preferences, increases the regressivity of a tax reform, independent of whether its revenues are recycled or not. Our results also support the idea that below (above) a certain level of high-wage labour supply elasticity, it is always (never) efficient to redistribute tax revenues progressively, meaning that it is possible to combine a double dividend with an equity goal. It proved more difficult to replicate propositions involving very specific market conditions, such as the Hosios condition. Altogether, we thus find that some results of the original model are more robust to the new modelling framework than others.

Changing the methodological lens leads to confrontation with additional theoretical questions, for instance, regarding monetary flows. These originate from the challenge of establishing a stable equilibrium. Fluctuations around a pseudo-equilibrium make it more difficult for the ABM to formulate specific propositions. While this might be seen as a weakness of agent-based approaches, it is questionable whether real economies are ever in equilibrium, thus highlighting the potentially low external validity of GEM results for a low-carbon transition.

Certain modelling choices, especially regarding stock-flow consistency, can affect the results tremendously. For instance, the decision to channel profits and vacancy costs back to households as a dividend increases the overall progressivity of a tax reform, because household income depends relatively less on wages. Another area where the ABM requires additional assumptions beyond the GEM concerns the sequence of actions and behaviours. Thus, the agentization process confronts modellers with questions about the interpretation of economic theory, which do not come up when solving a system of equations simultaneously or working from an assumed equilibrium. An ABM can thus help to go beyond marginal analysis by analysing the complex economic dynamics resulting from the stringent climate policies that are required for a deep decarbonisation of our economies.

References

Aubert, D. and Chiroleu-Assouline, M. (2019). Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82.

Bosello, F., Carraro, C., and Galeotti, M. (2001). The double dividend issue: modeling strategies and empirical findings. *Environment and Development Economics*, 6(1):9–45.

Bovenberg, A. (1999). Green tax reforms and the double dividend: an updated reader's guide. *International tax and public finance*, 6(3):421–443.

Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., and van den Bergh, J. (2020). A review of agent-based modeling of climate-energy policy. *Wiley Interdisciplinary Reviews: Climate Change*, 11(4):e647.

Farmer, J. D., Hepburn, C., Mealy, P., and Teytelboym, A. (2015). A third wave in the economics of climate change. *Environmental and Resource Economics*, 62(2):329–357.

Foramitti, J. (2021). Agentpy: A package for agent-based modeling in python. *Journal of Open Source Software*, 6(62):3065.

Freire-González, J. (2018). Environmental taxation and the double dividend hypothesis in CGE modelling literature: A critical review. *Journal of Policy Modeling*, 40(1):194–223.

Gerst, M. D., Wang, P., Roventini, A., Fagiolo, G., Dosi, G., Howarth, R. B., and Borsuk, M. E. (2013). Agent-based modeling of climate policy: An introduction to the engage multi-level model framework. *Environmental modelling & software*, 44:62–75.

Goulder, L. H. (1995). Environmental taxation and the double dividend: a reader's guide. *International tax and public finance*, 2(2):157–183.

Guerrero, O. A. and Axtell, R. L. (2011). Using agentization for exploring firm and labor dynamics. In *Emergent results of artificial economics*, pages 139–150. Springer.

Hosios, A. J. (1990). On the efficiency of matching and related models of search and unemployment. *The Review of Economic Studies*, 57(2):279–298.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., and Stern, N. (2018). Making carbon pricing work for citizens. *Nature Climate Change*, 8(8):669–677.

Maxim, M. and Zander, K. (2019). Can a green tax reform entail employment double dividend in European and non-European countries? A survey of the empirical evidence. *International Journal of Energy Economics and Policy*, 9(3):218–228.

Pearce, D. (1991). The role of carbon taxes in adjusting to global warming. *The economic journal*, 101(407):938–948.

Rengs, B., Scholz-Wäckerle, M., and van den Bergh, J. (2020). Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. *Journal of Economic Behavior & Organization*, 169:332–368.

Saltelli, A. (2002). Making best use of model evaluations to compute sensitivity indices. *Computer physics communications*, 145(2):280–297.

Sobol, I. M. (2001). Global sensitivity indices for nonlinear mathematical models and their monte carlo estimates. *Mathematics and computers in simulation*, 55(1-3):271–280.

Appendix 4.A Adjustment of income tax rates

A&CA allow the changes in income tax rates after a compensated tax reform to differ according to the following rules:

$$d\tau_L = -\left(1+\gamma\right)da \tag{4.33}$$

and

$$d\tau_H = -\left(1-\gamma\right)da \tag{4.34}$$

where $-da$ indicates the average labour tax rate variation. It is defined as:

$$da = \left(\frac{G^*_{\tau_D}}{(1-\gamma)G^*_{\tau_H} + (1+\gamma)G^*_{\tau_L}}\right) d\tau_D \tag{4.35}$$

Appendix 4.B Profit maximisation

The first order conditions, i.e. the first derivatives of the profit function for v_t and H_t yield (This is not derived in A&CA):

$$(1-\xi)\alpha p_y H^{1-\alpha}\left(\omega N_L^{\xi} v^{-\xi}\right)^{\alpha} v^{\alpha-1} = (1-\xi) w_{L,t-1}\omega N_L^{\xi} v^{-\xi} + c \tag{4.36}$$

from $\frac{\delta\Pi}{\delta v} = 0$, and

$$H = \left[\frac{(1-\alpha)\,p_y}{w_{H,t}}\right]^{\frac{1}{\alpha}} \omega N_L^{\xi} v^{1-\xi} \tag{4.37}$$

from $\frac{\delta\Pi}{\delta H} = 0$. By inserting (27) into (26) we obtain v_t^{opt}.

Appendix 4.C Optimal demand

Uncompensated optimal demand for C and D in the GEM are defined as:

$$C^{*} = (1-\sigma)\left[I_i - (1+\tau_D)\bar{D}\right] \tag{4.38}$$

and

$$D^{*} = \frac{\sigma}{(1+\tau_D)}\left[I_i - (1+\tau_D)\bar{D}\right] + \bar{D} \tag{4.39}$$

Appendix 4.D Proposition 1

Results of an uncompensated pollution tax of 1%, as used by the authors of the original paper in their simulations:

Table 4.11: Results of an uncompensated pollution tax ($\tau_D = 0.01\%$)

Z	Δu	ΔH	$\Delta C^D/\Delta C^S$	$\Delta D^D/\Delta D^S$	ΔY^S_{total}	$\Delta \frac{L}{H}$	ΔMP_L	ΔMP_H	ΔI_L	ΔI_H
0	-4.00	0.14	0.50/0.55	0.34/0.39	0.51	0.90	-0.53	0.37	0.12	0.53
0.01	2.22	-0.16	-0.30/-0.31	-0.19/-0.20	-0.28	-0.28	0.17	-0.12	0.01	-0.34
0.1	-0.35	-0.14	0.03/-0.15	0.06/-0.12	-0.14	0.19	0.20	0.00	0.34	-0.27

Note: 500 period average, difference in no-tax versus tax scenario. All changes given in percentage. $\tau_D = 0.01\%$, $\bar{D} = 0$ and $\eta_H = 0.5$.

Appendix 4.E Proposition 2

Table 4.12 shows the effects of an uncompensated tax reform under the conditions of Proposition 2 on purchasing power of high- and low-wage households.

Appendix 4.F Perfect substitution condition

The perfect substitution condition used in Propositions 2 and 4 refers to a situation without labour substitution. In the GEM this point is defined where the high-wage labour supply elasticity (η_H) equals the reaction of low-wage labour. As the latter hinges on indirect effects in the ABM, it cannot be determined easily. We thus check how the ratio of low- to high-wage labour changes

Table 4.12: Effects of an uncompensated pollution tax on purchasing power

η_H	$\beta < \xi$ high/low	$\beta = \xi$ high/low	$\beta > \xi$ high/low
0.3	-0.56/-0.49	-0.83/-0.78	-3.57/-2.25
0.5	-0.56/-0.48	-0.83/-0.84	-0.29/-1.36
0.63	-0.73/-0.76	-0.92/-0.81	-2.02/-0.39
0.8	-0.76/-0.80	-1.53/-1.03	-2.39/-0.29

Note: First value refers to high-, second value to low-wage households. 1000 periods, 500 period average of no-tax versus tax scenario. $\tau_D = 1\%$.

after each type of tax reform, depending on various levels of high-wage labour supply elasticity (η_H). Figure 4.10 shows the results for an uncompensated and a compensated tax reform when the pollution tax rate is set at 0.01 or 1%.

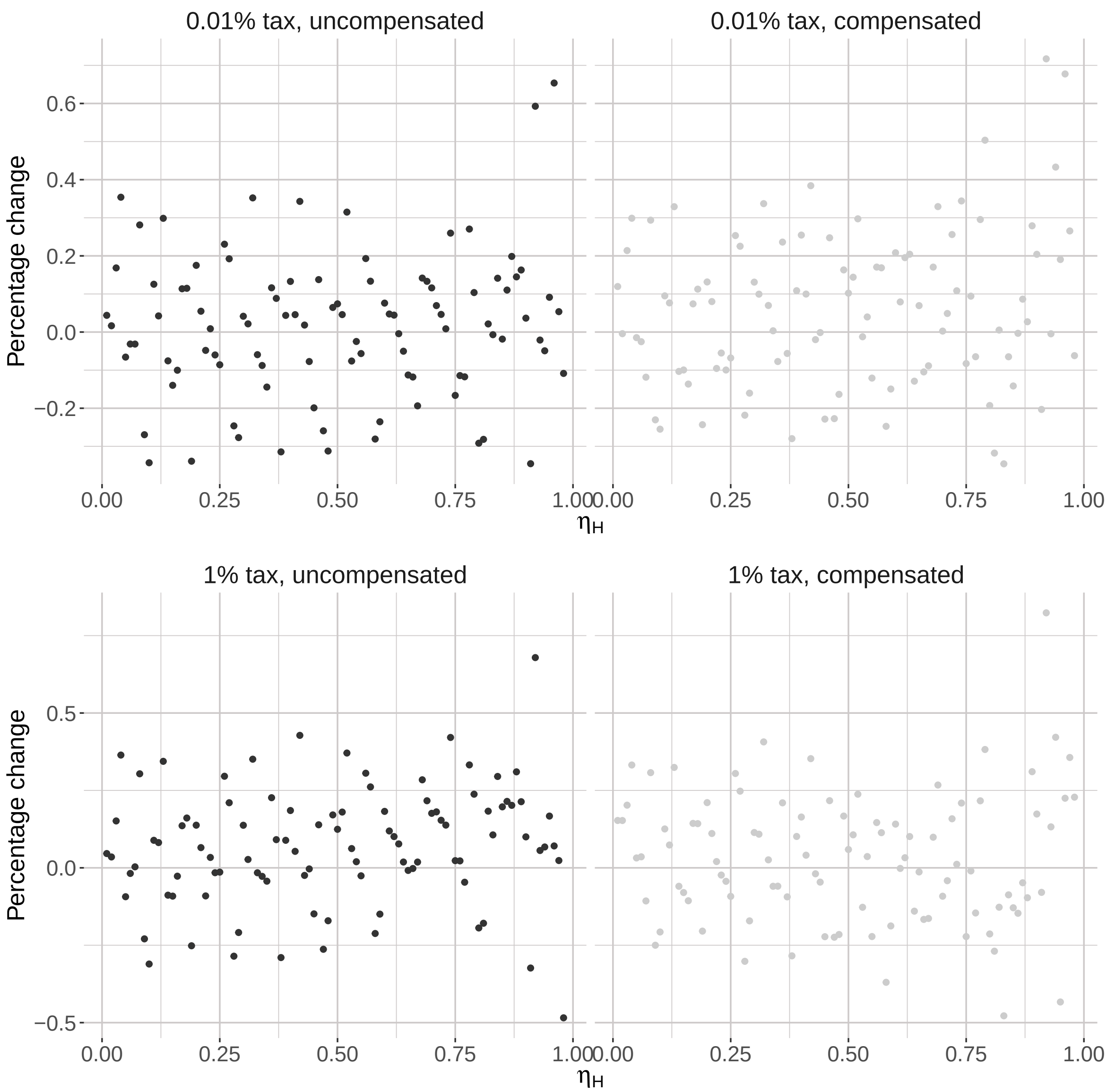


Figure 4.10: Change in ratio of low- to high-wage labour inputs at different levels of high-wage labour elasticity

As both figures show, the relationship between η_H and the change in labour ratio is highly non-linear. To meet the perfect substitution condition, the change in the labour ratio should be equal to zero. Under an uncompensated tax reform, this is approximately given for $\eta_H = 0.63$. Under a compensated tax reform with a 1% tax rate, $\eta_H = 0.61$ prevents shifts between the two labour types.

For Proposition 4, the perfect substitution condition must old for various levels of tax rates. Figure 4.11 shows the relationship between η_H and the labour ratio under a compensated tax reform for different levels of pollution taxes. The red dots indicate the level of η_H chosen for our respective simulations.

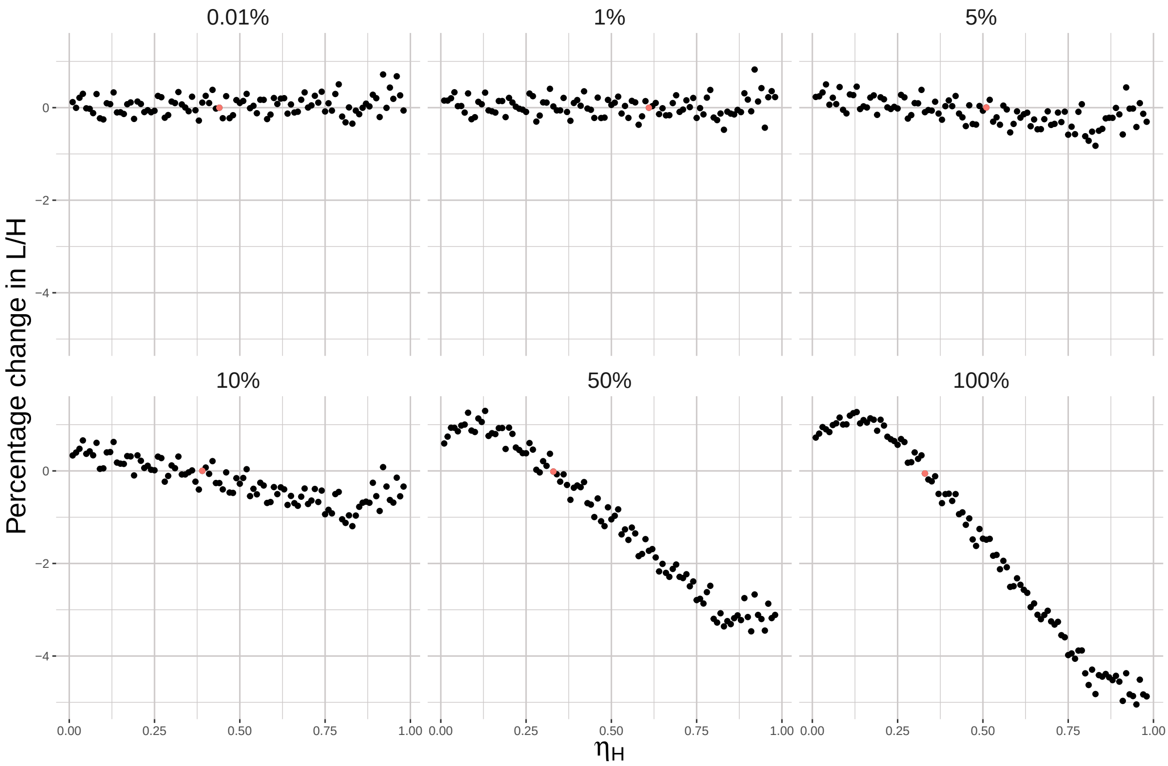


Figure 4.11: Change in ratio of low- to high-wage labour inputs under a compensated tax reform for different levels of high-wage labour elasticity and tax rates

Chapter 5

A behavioural-evolutionary agent-based model of environmental tax reform with green and leisure preferences

5.1 Introduction

We develop an agent-based model of environmental tax reform (ETR), investigating the effects of such a policy under a behavioural-evolutionary scenario. To reflect this behavioural-evolutionary perspective, the model includes four key novelties that go beyond existing models of ETR, which mostly focus on fully rational, representative agents. These are (i) bounded rationality, (ii) agent heterogeneity, (iii) social influence on consumption preferences, and (iv) an activity-based lifestyle approach.

An environmental tax reform, defined as a revenue-neutral tax shift towards carbon dioxide emissions, offers many design options. This holds particularly for the use of its revenues. We analyze three popular recycling channels for carbon tax revenues: (1) a reduction in income tax rates, (2) an equal per capita climate dividend, and (3) earmarking for green innovation. Policy evaluation is focused on four main outcomes: (i) environmental impact, (ii) overall economic welfare, (iii) employment, and (iv) innovation.

A long-standing motivation for ETR is a potential *strong double dividend* of simultaneous environmental and economic improvement (Goulder, 1995). In its strong form, the double dividend implies environmental improvement combined with economic benefits compared to a situation with no tax reform. In this case the policy can be motivated purely based on efficiency grounds, regardless of any environmental benefits. We assess the potential for an environmental dividend by measuring the change in fossil energy use during production and consumption. We consider two indicators for a potential economic dividend. First, overall social welfare measured through average purchasing power, and second, employment effects. We also consider distributional impacts on purchasing power and employment through an assessment by household types.

Since households in our model differ along various characteristics, we represent a population of heterogeneous agents. We assume that they can interact with each other and allow for imitation of peers in certain experiments. This setup is in line with evolutionary economic approaches, describing the dynamics of agent populations using system dynamics or agent-based modelling. The model relies on insights from behavioural economics and psychology, including habitual decision-making on the household and on the firm side. Agents make conscious and rational choices only when they are triggered and without full information or perfect foresight. Otherwise, they follow established routines. Specifically, individuals are triggered by a change in employment or by insufficient income to afford their habitual consumption (e.g. because of price increases). In this case they will revise their consumption and labour decision. Firms are modelled as *satisficing* organizations whose innovation and profit maximization is triggered by stagnating or falling profits. Following this behavioural-evolutionary approach, we are able to incorporate some behaviours which are relevant, but rarely modelled by studies of ETR (Klein and van den Bergh, 2021).

The model takes a *lifestyle* or *activity-based* approach, meaning that households make allocation decisions starting from a fixed time budget. As motivated in Chapter 2, including a time dimension is highly relevant when we talk about trade-offs between labour and consumption time. In addition to work time, individuals need time for consumption, and also for unpaid work. These time requirements can differ depending, for example, on social norms or cultural context.

In the underlying model, lifestyle differences are reflected through consumption of three types of goods, which are produced in three sectors with different production technologies. In particular, the sectors vary in labour- and energy-intensity during production. Furthermore, the goods differ in terms of time and energy requirements during consumption. The goods include a conventional "polluting" good (D), a similarly produced, but more energy-efficient version of this good (C - clean), and a sufficiency good (S), which is characterized by more consumption time and labour-intensity, compared to energy use.

These categories can be interpreted broadly as manufactured goods for C and D, whereas S represents mostly the service sector (repair or reuse of existing goods, or experience-oriented activities). One motivation for this theoretical approach is the relevance of the intensive margin of labour supply. Given that consumption and care work take time, it is not only important whether or not an individual works, but also how much of their time they allocate to work. Consumption time becomes even more relevant, if time-saving behaviours are characterised by higher energy use.

Households are heterogeneous in the model with respect to workforce participation and sector of employment, education level, gender, and geographical location (urban vs. rural). One part of the population engages in paid labour, whereas another does not (students, retirees, housekeepers). Education is used as a proxy for high- and low-wage individuals, who possess different skill sets. Labour markets are separated by skill and sector. The producer of the sufficiency good acts in a distinct labour market from the producers of C and D. The former broadly represents the service sector, while the latter depicts manufacturing and industry. We allow for unemployment in each of the four separate labour sub-markets.

The gender distinction reflects differences in time availability and sector of employment. As women and men on average spend different amounts of time on unpaid work, they have distinct time budget constraints for remaining activities. Regarding employment sectors, the share of women working in the service sector is higher than for men. The model further distinguishes between rural and urban households, who are assumed to have different levels of subsistence polluting consumption. This reflects variation in energy use requirements of urban and rural households for heating or commuting, for example.

These dimensions of heterogeneity reflect important division lines in the current discussion on fairness of climate policy and horizontal (i.e. non-income-related) inequalities. The constraints of unpaid work are closely linked to gender inequality, a topic that has been largely unexplored in the discussion of climate mitigation policies. Acknowledging typical employment sectors for distinct household types also allows us to combine economic effects of an ETR on the supply and demand side. The policy does not only affect consumption choices, but can also shift the likelihood of unemployment between groups who work in different sectors.

Finally, the model takes up ideas from evolutionary economics by allowing for social interaction between households. In particular, we focus on imitation. In this social setting, we assume that household preferences are affected by the consumption of a reference group. Following Konc et al. (2021) we implement this interaction through a social multiplier in the utility function. Aspiration towards lifestyles of the wealthy is a widely observed social phenomenon. However, we assume that households do not only aspire the lifestyle of those with higher incomes, but of those who they can identify with on other levels. The reference group for each household are thus individuals with a higher income than themselves, but who are similar in terms of gender, geographical context and work sector.

The agent-based approach allows for theoretical investigations beyond a fully rational, atomistic *homo oeconomicus*. This level of complexity aids in understanding how a comprehensive policy unfolds in a complex socio-economic system. The model is developed for theoretical exploration and policy analysis, rather than for prediction. Nevertheless, key variables and assumptions are validated using empirical data from Germany. Hence the results should be understood in this context.

The remainder of the paper is structured as follows. Section 5.2 describes the sequence and main equations of the model. Section 5.3 explains the use of empirical data for validation. Section 5.4 presents the results of the policy experiments. Section 5.5 concludes.

5.2 The model

5.2.1 Model sequence

The ABM generally has a similar sequence as our previous model in Chapter 4. However, it comes with a few additions we will describe below. As there is more heterogeneity on the household and firm sides, there are now four instead of two labour markets. We model frictions through search-and-matching processes in each of them. Figure 5.1 shows the features of these four markets.

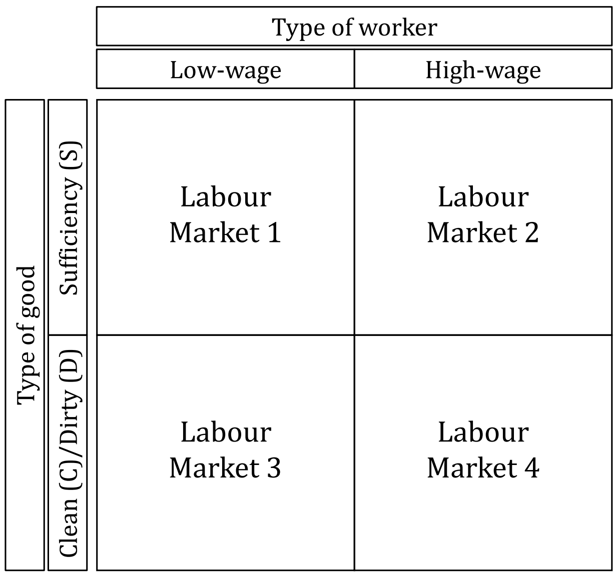


Figure 5.1: The model's four labour markets

There are also some additional steps in the model sequence (see Figure 5.2). The most important addition is innovation (step 2). If a firm is triggered by falling profits, it will attempt to innovate at the beginning of the next period. Innovation will be successful with a certain probability (ι) and can be stirred towards either one of the input factors (*process innovation*): low-wage labour, high-wage labour or energy, or towards energy-efficiency of the final product (*product innovation*). If firms are losing market share, they will aim for product innovation. Otherwise, they target the input factor with the highest cost share. If successful, the innovation process for the three production factors is defined as:

$$A_{m,t} = A_{m,t-1} \left[1 + \left(\frac{1}{A_{m,t-1}} \right)^{I_{R\&D,j,t}} \right] \tag{5.1}$$

$A_{j,t}$ is the new factor productivity, $A_{j,t-1}$ is the factor productivity prior to the innovation process, and $I_{R\&D,j,t}$ is the amount of investment in innovation. Thus, innovation becomes more difficult with increasing factor productivity, but it is also increasing in the amount of R&D investments. Firms re-invest any profits, if they make any. For energy consumption during use of a good, the goal is to reduce the respective energy-intensity, $e_{j,t}$. The innovation process is thus modelled as follows:

$$e_{j,t} = e_{j,t-1} \left(1 - e_{j,t-1}^{I_{R\&D,j,t}} \right) \tag{5.2}$$

$e_{j,t-1}$ is the energy-intensity of good J prior to innovation and $I_{R\&D,j,t}$ is again the amount of investment in innovation.

After a firm innovates, it moves on to updating its wage rates and maximizing profits. It does so by deciding on the optimal amount of energy and the number of vacancies to post in both labour markets (low- and high-wage) based on previously observed matching rates. Innovation thus automatically leads to profit maximization. However, there is another trigger for a firm to optimize: if it has no applicants. In this case the firm also revises its offered wage rates and determines optimal factor inputs. If a firm's profits are growing and it has applicants, it will merely try to replace potentially lost labour force from the previous period.

There are a number of potential triggers for households to update their decisions as well. During initialization all households and firms perform an optimization to make sure that each agent has a general idea about their optimal lifestyle/production. In general, households are habitual, meaning that they will try to consume the same amounts as in the preceding period. However, if a worker loses their job, be it through random or conscious termination, they are triggered to reassess their labour and consumption decision in line with their preferences. If previous consumption patterns are no longer attainable to an individual even though they are employed, they have to scale down the amount of goods they purchase. As a result they become discontent in our model. Three periods of discontent will lead to the decision of an individual to terminate their job, if unemployment benefits or wages in their labour market are sufficiently high.

Firms and households meet at one of the four labour markets: low-wage or high-wage sufficiency sector and low-wage or high-wage C/D. Job seekers and vacancies are matched within their respective market with a certain probability. The probability of a vacancy to be filled can be expressed

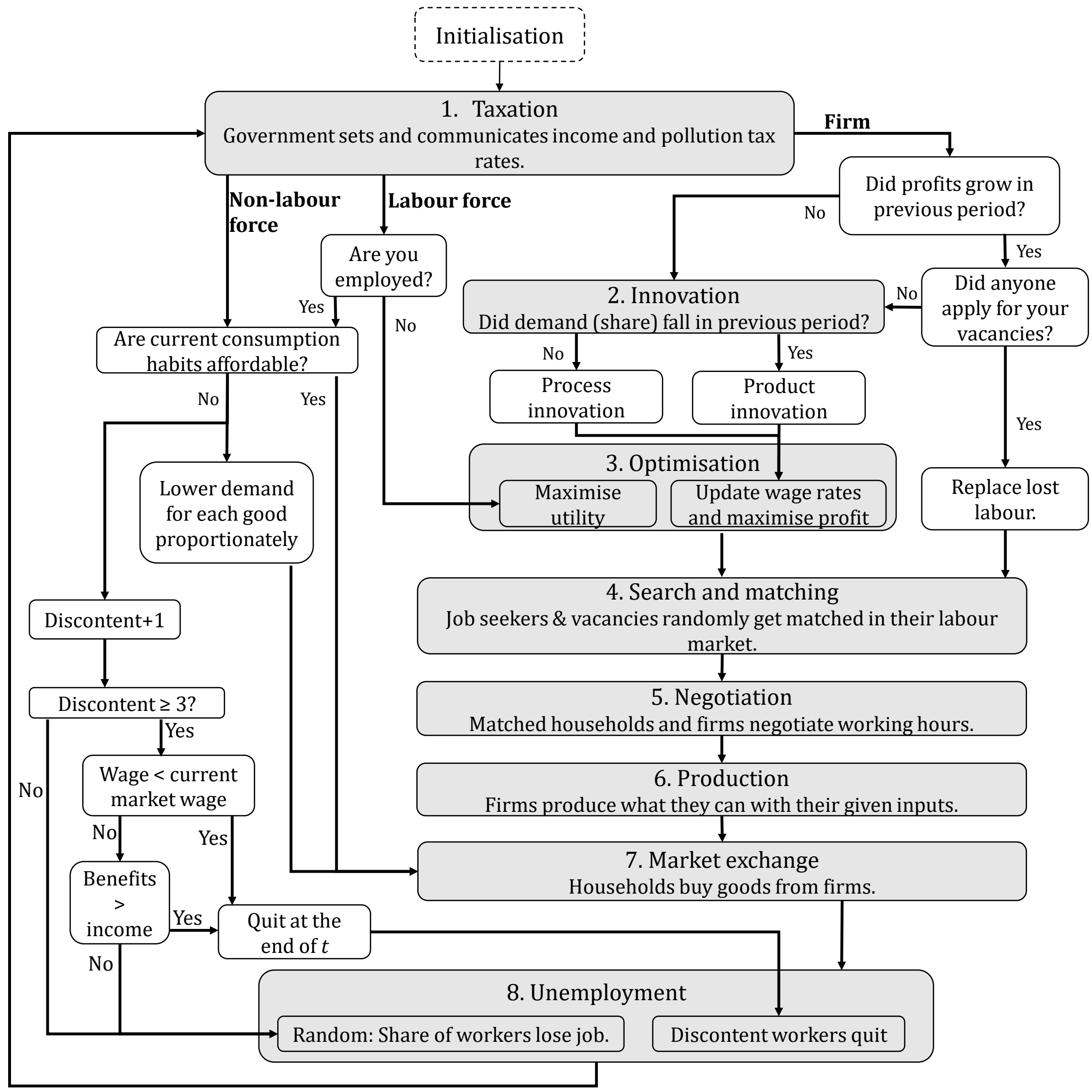


Figure 5.2: Model sequence

Note: Grey boxes indicate agent decisions, actions and interactions, which can be triggered by factors in the white boxes.

through the matching function, defined as:

$$M = min\left(\Omega\left[\frac{U}{v}\right]^{\xi}, 1\right) \tag{5.3}$$

where U is the number of job seekers and v is the number of vacancies posted. Ω and ξ take values in $(0, 1]$. The matching probability M is increasing in U and decreasing in v. Hence, it may be interpreted from the point of view of the firm as more job seekers per vacancy increase the likelihood of a firm to fill its vacancies. For job seekers more competition has the opposite effect, of course.

Contrary to the model in Chapter 4, firms and workers do not negotiate wages. The firm sets a wage rate when posting the job, but workers can negotiate their working time. The firms optimal work time per employee is defined as:

$$wt_{j,opt} = min\left(\frac{J_{opt} - J_S}{J_M}, WT_{max}\right) \tag{5.4}$$

where J_{opt} is the firm's optimal overall (low- or high-wage) labour input, and J_S and J_M are their existing stock of labour and new workers matched of the respective type. WT_{max} is the legal work time maximum a firm can ask from its employees which is currently set at 8 hours. Resulting working time after a successful match is defined as:

$$wt_i = wt_{i,opt} + \beta_j(wt_{j,opt} - wt_{i,opt}) \tag{5.5}$$

where $wt_{i,opt}$ is the worker's desired work time, $wt_{j,opt}$ is the firm's desired work time and β_j reflects the firm's bargaining power.[1]

After the negotiation firms know their available production inputs and households know their income. Energy supply is exogenous to the model and available at a fixed price, p_E. The firms produce as much as they can. Households will adjust demand downwards, if their real income falls. Similarly, they will decrease (increase) consumption time proportionately, if they end up working more (less) than previously anticipated. Households and firms exchange goods. As the firms have other production costs beyond labour, we need to specify these monetary flows as well. The cost of vacancy posting goes is relatively small and goes back to all households directly, as in the model of Chapter 4. The expenditure on energy turns into additional demand for the three goods. It can be interpreted as exports, if one assumes that energy is bought from another economy, for example. Another viewpoint would be that a capitalist consumes the energy rents.

Finally, there is another major step added on top of the model sequence in Chapter 4: Unemployment. A share of work contracts is randomly dissolved at the end of each period. In addition, discontent workers may quit.

5.2.2 The household problem

Each household is equipped with certain sector-specific skills (low- or high-wage, S or C/D) and time availability. While each individual has the same amount of time, some are faced with more binding unpaid work and hence less available time to decide upon than others. Individuals then need to decide about their labour supply, consumption time and consumption expenditure. We assume that every household initially has an idea of their desired lifestyle (initial optimisation).

[1] Note that the firm cannot ask an employee to work more than 8 hours, but an employee willing to supply more labour than that is able to.

They re-evaluate their lifestyle under the above-mentioned conditions. Household preferences are represented through the following nested CES utility function:

$$U_{i,t} = \left[\alpha_i \left(t_{s,i,t} u_s S_{i,t}\right)^{\sigma} + (1-\alpha_i)\left(\epsilon_i \left(\left(t_{c,i,t} u_c + o_c\right) C_{i,t}\right)^{\delta} + (1-\epsilon_i)\left(\left(t_{d,i,t} u_d + o_d\right)\left(D_{i,t} - \bar{D}_i\right)\right)^{\delta}\right)^{\sigma/\delta}\right]^{1/\sigma} \quad (5.6)$$

In this case, utility of individual i in period t ($U_{i,t}$) is achieved through both ownership (o_j) and use (t_j) of goods C ("clean" - or more energy-efficient) and D ("dirty" - or conventional), and through use of S ("sufficiency"). Note that ownership of S without spending time on using it does not increase well-being. A subsistence level of dirty consumption ($\bar{D}$) exists, representing goods needed for fulfilment of basic needs, such as shelter, heating/cooling or food intake. We assume that this subsistence consumption is purely material and requires no considerable consumption time. It is assumed to be higher in rural areas than in urban areas.

Each of the goods has a use characteristic (u_j) that defines the amount of time needed to reach a comparable level of utility. It is for this consumption-time characteristic, and the fact that good S is "less material", that it is helpful to think about these goods more as lifestyles than items. For certain categories, such as travel, the trade-off between time required for a trip and energy use is rather obvious. For other consumption categories this is less clear. We do not claim that all goods circulating in the economy can be classified sharply into these three categories. We are rather assuming, that D represents the main input into an energy-intensive, but time-saving lifestyle, C a somewhat "greener" version of this lifestyle, whereas S represents fundamentally different consumption behaviours to fulfil the same needs.

Since this is a key aspect of our model, let us provide some examples. Regarding food, D could represent a meat-based consumption, C a vegetarian diet, and S a vegan diet. Living a vegan lifestyle can be seen as more time-intensive in terms of food and information sourcing in a society where a meat-based diet is the norm. Another example could concern the use of household appliances, for example to dry laundry. Good D could represent an energy-intensive tumble drier, C would then be a more energy-efficient model, and S would be hanging laundry by hand to air dry.

The D-C-S distinction is probably clearest for the case of mobility. Commuting to work with a conventional diesel or petrol SUV represents the extreme of a fast and energy-intensive lifestyle (D). Electric vehicles, smaller cars or even motorcycles could fall into category C - they require approximately the same amount of time to get from A to B, but with less energy consumption. Good S could be interpreted as biking, walking, or taking using public transportation, for example. While C is a somewhat greener version of a polluting lifestyle (D), S represents a sufficiency-oriented consumption type that often requires a different organisation of consumers' lives.

As apparent from the preference structure, consumption is weighted according to two value scales.

Individuals have different levels of materialism ($1-\alpha_i$) and environmentalism (ϵ_i). Materialism refers to a preference for material consumption goods (high energy content) over engagement in activities (sufficiency or low-energy consumption). ϵ_i represents an individual i's environmentalism. The more pro-environmental their values, the more they prefer C over D. Both of these preference parameters can be written including a social multiplier effect, following Konc et al. (2021). α would then be defined as (same equation holds for ϵ_i):

$$\alpha_i = (1-\zeta)\, v_i + \zeta SI_i \tag{5.7}$$

where SI_i is the behaviour individual i observes in its peers. v_i represents the true materialistic values of individual i and ζ is the strength of social influence[2]. Social influence for α_i is defined as:

$$SI_i = \frac{1}{N_i}\sum_{n=1}^{N_i} \frac{t_{S,n}S_n}{t_{S,n}S_n + t_{C,n}C_n + t_{D,n}(D_n - \bar{D})} \tag{5.8}$$

where N_i is the number of households with similar characteristics, but higher income than individual i (the reference group). It is the average share of sufficiency consumption of the reference group. For ϵ_i, SI_i is the share of clean consumption (C) out of total consumption ($C + D - \bar{D}$).

The purchasing price as well as energy costs for use of the purchased goods enter the budget constraint of the household, which we define as:

$$(1-\tau_{i,t})\, w_{i,t} wt_{i,t} = p_D \bar{D}_i + \sum_{J \epsilon (D-\bar{D},C,S)} \left(p_{j,t} + (1+\tau_{E,t})\, p_{E,t} t_{j,i,t} e_j\right) J_{i,t} \tag{5.9}$$

The left hand side represents net wage income of individual i in period t. The right hand side is the expenditure for subsistence consumption ($p_D\bar{D}_i$) plus the costs of buying and consuming goods ($J_{i,t}$) beyond that. $p_{j,t}$ is the purchase price of good J, $(1+\tau_{E,t})p_{E,t}$ is the energy price per unit including a potential carbon tax, e_j is the energy use per unit of consumption time of good J (i.e. its energy efficiency). Finally $t_{j,i,t}$ is the amount of time individual i decides to use good J. It is important to note that use costs from using the "dirty" good D only accrue above the subsistence level $\bar{D}$, because they are linked to time spent on consumption. We further assume that energy use per time unit is increasing in expenditure on the respective goods used. This can be interpreted either as simultaneous use of multiple goods, or as an often higher energy demand of more expensive versions of a certain good, for example linked to higher weight or better performance.

Finally, the household time constraint is defined as:

$$T = U_i + wt_{i,t} + t_{S,i,t} + t_{C,i,t} + t_{D,i,t} \tag{5.10}$$

[2] In the scenario without social influence, $\alpha = 0.5$ and $\epsilon = 0.5$

While overall time endowment, T, is the same for every individual, the choice between labour ($wt_{i,t}$) and consumption time ($t_{j,i,t}$) is restricted by heterogeneous levels of unpaid work U_i. See Appendix 5.A for more details.

5.2.3 The firm problem

Each of the three sectors is represented by one firm, j (producing good j). These firms all produce with a CES production function and three inputs: low-wage labour, high-wage labour and (fossil) energy.

$$y = f(L, H, E) = P_j\left[s_{H,t}(A_{H,t}H)^\rho + s_{L,t}(A_{L,t}L)^\rho + s_{E,t}(A_{E,t}E)^\rho\right]^{\frac{1}{\rho}} \tag{5.11}$$

$$s_{L,t} + s_{H,t} + s_{E,t} = 1 \tag{5.12}$$

where $A_{m,t}$ represents the technological state of the art of production factor $m \epsilon (L, H, E)$ in period t and $s_{m,t}$ the factors' cost shares in production. P_j is an overall productivity factor which we use to calibrate the model.

As mentioned earlier, the firms are satisficers. If their profits are not falling and they have applicants for their vacancies, they do not change their production inputs or innovate. The profit function of firm j is defined as follows:

$$\Pi_{j,t} = p_{j,t}y_{j,t} - (w_{L,t}L + w_{H,t}H + (1 + \tau_{E,t})p_E E + c_H v_{H,j,t} + c_L v_{L,j,t} + I_{R\&D,j,t}) \tag{5.13}$$

where $p_{j,t}y_{j,t}$ are the revenues if all production is sold, $w_{H,t}$, $w_{L,t}$ and p_E are the input factor prices, and $\tau_{E,t}$ is the carbon tax level in period t, levied as an upstream tax on fossil energy. $c_H v_{H,j,t}$ and $c_L v_{L,j,t}$ are the costs of posting high- and low-wage vacancies (low compared to wage costs) and $I_{R\&D,j,t}$ are potentially accruing investments in product or process innovation in period t.

The overall amount of low- and high-wage labour hours depends on the firm's existing stock of labour, their new successfully matched vacancies and the average work time of an employee. If a firm is triggered by falling profits or zero labuor supply, it updates its wage rates and maximises profit. See Appendix 5.B for more details and first-order conditions for a profit maximum.

5.3 Data

To have an empirical basis for our household typology, we build on data from a survey conducted in Germany in early 2020 (pre-pandemic) by the ReZeitKon project, which combines information on work time and individual demographics with detailed data on consumption habits, including sufficiency behaviours (Geiger et al., 2022). This survey provides the basis for our representative household groups. Table 5.1 provides a summary of the relevant variables. We group the sample

Table 5.1: Household typology

			Sector	Nb	Freq.	Share in %	Care work (h/d)	Paid work (h/d)	Leisure preference (%)	Share of D	Share of C	Share of S
High-wage	Female	Urban	C/D	1	2	0.13	1.00	5.64	0.00	66.67	14.81	18.52
			S	2	16	1.02	2.11	5.07	68.75	35.89	25.36	38.76
		Rural	C/D	3	10	0.63	4.75	5.40	40.00	58.55	17.76	23.68
			S	4	51	3.24	3.68	4.64	47.06	43.88	22.34	33.78
	Male	Urban	C/D	5	11	0.70	1.86	5.43	36.36	45.40	20.25	34.36
			S	6	18	1.14	1.76	5.29	44.44	50.42	23.31	26.27
		Rural	C/D	7	21	1.33	2.49	5.48	28.57	45.67	21.00	33.33
			S	8	42	2.67	2.25	5.58	45.24	41.00	23.00	36.00
Low-wage	Female	Urban	C/D	9	9	0.57	1.98	5.02	11.11	42.86	27.55	29.95
			S	10	45	2.86	2.86	4.70	37.78	45.23	20.89	33.88
		Rural	C/D	11	87	5.52	3.83	4.68	26.44	50.99	17.98	31.03
			S	12	264	16.76	4.92	4.35	26.89	49.86	18.28	31.85
	Male	Urban	C/D	13	28	1.78	1.32	5.53	32.14	49.06	19.50	31.45
			S	14	46	2.92	2.01	5.38	50.00	45.74	21.31	32.95
		Rural	C/D	15	193	12.25	2.43	5.44	27.46	52.77	18.13	29.10
			S	16	187	11.87	2.23	5.15	26.74	50.68	17.98	31.34
Non-WF	Fem	Urban	-	17	45	2.86	4.61	-	-	40.97	18.92	40.10
		Rural	-	18	268	17.02	4.58	-	-	41.64	19.18	39.18
	Male	Urban	-	19	42	2.67	1.81	-	-	46.99	18.42	34.59
		Rural	-	20	190	12.06	2.11	-	-	47.43	16.16	36.40
					1,575	100%						

Note: High-wage = tertiary education; non-workforce includes students, retirees and housekeepers; urban = more than 500k inhabitants; C/D = works in industry/manufacturing, construction or logistics; Nb = number of the HH type; Freq = frequency of observations; leisure preference = stated to prefer more free time over a salary raise, C,D,S = share of consumption behaviours falling in our goods categories C,D or S. Non-WF=non-workforce.

based on whether an individual is in the work-force or not, their level of education as a proxy for the hourly wage category, their gender, and the degree of urban environment as a proxy for the level of subsistence polluting consumption. We then calculate the average levels of unpaid and paid work for each of these groups. Unpaid work includes care and house work. As Table 5.1 shows, women engage considerably more in unpaid work than their male counterparts for almost all groups, whereas the differences in paid work are smaller, especially among highly-educated groups.

In the ReZeitKon questionnaire, respondents are asked how often they perform a number of consumption behaviours. We classified those behaviours according to our goods distinction as either dirty, clean or sufficiency consumption and constructed an index for each group. To do so, we sum up the number of consumption behaviours performed by each individual per category and then compared the mean of each category relative to the other two consumption categories by household type[3]. The columns titled C, D and S in Table 5.1 show the resulting share of consumption behaviours . Finally, the survey asks whether participants would prefer additional time off-work over a salary raise. The "leisure preference" column in Table 5.1 displays the share of individuals who answered yes to that in each group.

On the production side, we consulted the literature on labour- and energy-intensity of different

[3]see Appendix 5.C for the allocation of different consumption behaviours into *dirty*, *clean* and *sufficient*.

sectors in Germany in order to define the production parameters. We are using a non-nested production function, following Van der Werf (2008). They estimate elasticities for differently nested CES production functions typically used in climate policy modelling and find that for Germany a nested production function does not fit any better than a non-nested one.

Welsch and Ochsen (2005) study input elasticities to production that include energy, low- and high-wage labour in the West-German industry. Their results show that low-wage labour is a Morishima complement to energy, i.e. the ratio of energy to low-wage labour increases when the energy price increases. The same ratio remains constant for high-wage labour, making low-wage labour a stronger complement to energy than is high-skilled. At the same time, energy acts as a substitute for both labour factors. The elasticity of substitution between low- and high-wage labour has widely been estimated to be around 1.5, but may in fact be nearer to 0.6-0.9[4]. We use a non-nested CES production function with a substitution elasticity of approximately 0.7 in our model.

Table 5.2: Energy-, labour- and time-intensity of the goods/lifestyles

		Dirty	**Clean**	**Sufficient**
		Materialistic		**Non-materialistic**
Production		High energy-intensity $s_E = 0.15$ Low labour-intensity $s_L = 0.55$ $s_H = 0.30$		Low energy-intensity $s_E = 0.05$ High labour-intensity $s_L = 0.60$ $s_H = 0.35$
Consumption		High energy-intensity $e_d = 0.8$ Low time-intensity $u_d = 1$	Medium energy-intensity $e_c = 0.5$ Low time-intensity $u_c = 1$	Low energy-intensity $e_s = 0.1$ High time-intensity $u_s = 2$
Examples	*Commuting:*	Combustion-engine car	Electric car	Public transport
	Food:	Meat-based	Vegetarian	Vegan
	Appliances:	Tumble-drier	Energy-efficient tumble-drier	Air drying laundry
	Vacation:	Air travel	Long-distance train ride	Regional cycling tour

Note: Production factor cost shares (s_m) based on Koschel (2000) and Welsch and Ochsen (2005). See Appendix 5.D for more detailed information on the calculation. The consumption parameters are not empirically based.

Table 5.2 shows the current parameter values for cost shares in production by sector[5], as well as the relationships between energy and time use that we are assuming. In particular, good D has the highest energy intensity per time unit (e_D) in our model, followed by C (e_C) and then S (e_S). However, the marginal utility per time unit spent on an activity with consumption goods C or D (u_C, u_D) is lower than for S (u_S).

Appendix 5.F gives an overview of all other parameter values used. The model is coded in Python, using the AgentPy framework (Version 0.1.5) by Foramitti (2021). Some analysis of the

[4] Some authors suggest considerable publication bias and problems in estimation techniques. Havranek et al. (2020) perform a meta-analysis where they correct for such biases, and find that the elasticity is around 0.6-0.9.

[5] More details on that also in Appendix 5.D.

output data is performed using R (Version 4.1.0). The code is available from the authors upon request.

5.4 Policy experiments

We perform and compare four main policy experiments. Each scenario includes the introduction of a carbon tax on energy use in period 500 out of 1000 model rounds in total. The tax rate is always set at 10%. However, the policies differ in terms of revenue use.

In the first case, carbon tax revenues are recycled back to workers through proportionate reductions in personal income tax rates, as suggested by many economists on efficiency grounds at least since the early 1990s (e.g.Pearce, 1991, Repetto and Dower, 1992, Aubert and Chiroleu-Assouline, 2019 to name only a few). Two problems with this recycling mechanism is that it tends to be regressive and that it shifts tax incidence to individuals outside of the labour force.

We address the regressivity problem by testing progressive income tax cuts, where tax rates are reduced more strongly for low-wage workers. An even more equitable policy scenario would include the needs of the non-working population. Therefor, we also examine a third option of using carbon tax revenues to pay an equal per capita climate dividend to each individual. This option has in fact been proposed to relieve lower-income households in practice, such as in the context of the German carbon tax (Edenhofer et al., 2019). As many researchers and practitioners have pointed out, the political acceptance of carbon taxation often hinges on its direct link to environmental purposes (e.g. Carattini et al., 2018, Douenne and Fabre, 2020 , Maestre-Andrés et al., 2021). Thus our last policy scenario considers earmarking the carbon tax revenues for energy-saving innovation. Figure 5.3 gives an overview of these four policy scenarios.

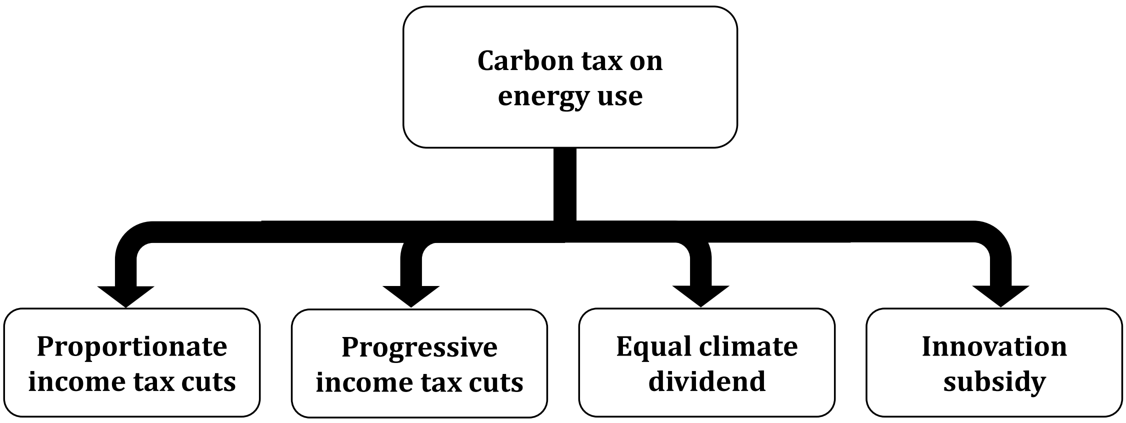


Figure 5.3: Revenue recycling scenarios

For each scenario we compare the baseline behaviour of the model without any policy intervention with the results under the implementation of the different policies. We then monitor four main outcomes. The first is total energy consumption, i.e. energy use during production and consumption of goods. The second measure is overall purchasing power, measured as compensatory variation, i.e. the additional income needed for all households to be able to afford their pre-policy consumption levels. A decrease in energy use paired with an increase in purchasing power are the condition for a double dividend. The third outcome is unemployment. A simultaneous reduction in unemployment and energy consumption would imply an *employment* double dividend. Fourth, we monitor if there is technological progress on energy- and labour-efficiency. We will compare these outcomes for cases with and without socially-embedded preferences. In addition, we will dedicate a subsection each to heterogeneity in green (non-materialistic and pro-environmental) preferences, and heterogeneity in preferences for leisure/consumption time. To make them more comparable, we display the main results for each setting together in Figure 5.8 at the end of this section and in detail in Appendix 5.7.

5.4.1 Results for independent agents

We begin with a model setting of isolated agents, who make their decisions independently. Table 5.3 shows our main results: the percentage change in overall purchasing power, unemployment rate and energy use after each policy, compared to the baseline scenario. The first two indicators represent a potential economic dividend, whereas the latter shows the potential for an environmental dividend.

Table 5.3: Policy outcomes

Revenue use	**Purchasing power**	**Unemployment**	**Total energy consumption**
Proportionate income tax cuts	0.28	-63.47	-25.68
Progressive income tax cuts	1.75	-40.75	-34.81
Climate dividend	20.07	107.87	267.12
Innovation subsidy	10.17	-75.59	-31.45

Note: Changes under various revenue-recycling options compared to the baseline (no policy) in percentage points. Tax rate, $\tau_E = 10\%$.

Average purchasing power (PP) increases in each policy scenario. The rise is particularly strong when revenues are used for a climate dividend to all households. However, this does not benefit all household types equally. High-wage earners in the energy-intensive sectors C and D suffer losses in PP across all policy scenarios. Households outside of the labour force face reductions in PP in all scenarios, except for the climate dividend. The negative impact on these benefit recipients is higher in both income tax cut scenarios than in the innovation scenario.

The largest gains in PP can be observed among high-wage employees in the low-energy sector (S). While these gains are similar in magnitude for men and women in urban areas, in rural areas they are around three times as high for men as for women. This is caused by a stronger increase in work time among men than women under the climate dividend. The reason is that more of these women's time is locked up in care work, so they have fewer possibilities to increase their participation in the labour market. In the innovation subsidy scenario, these men shift their consumption relatively more towards the less energy- but more time-intensive good S. The relatively high time constraint of unpaid work for women prohibits equivalent gains to their male counterparts in both scenarios. In this particular group, women spend about 64% more time on unpaid care work than men. For the urban counterpart this number is 20% (see Table 5.1), leading to a more equal effect on purchasing power.

The unemployment rate falls in three out of four scenarios. It more than doubles when revenues are used to pay out a climate dividend. However, unemployment is generally very low in our model, with the majority of rounds showing full employment. This can also be seen from Figure 5.4, which shows a more disaggregated picture of the labour market. The upper panel represents the unemployment rate (left) and average working time (right) by household type under four policy scenarios and the baseline. The lower panel displays incomes by household type for all individuals in the labour force[6].

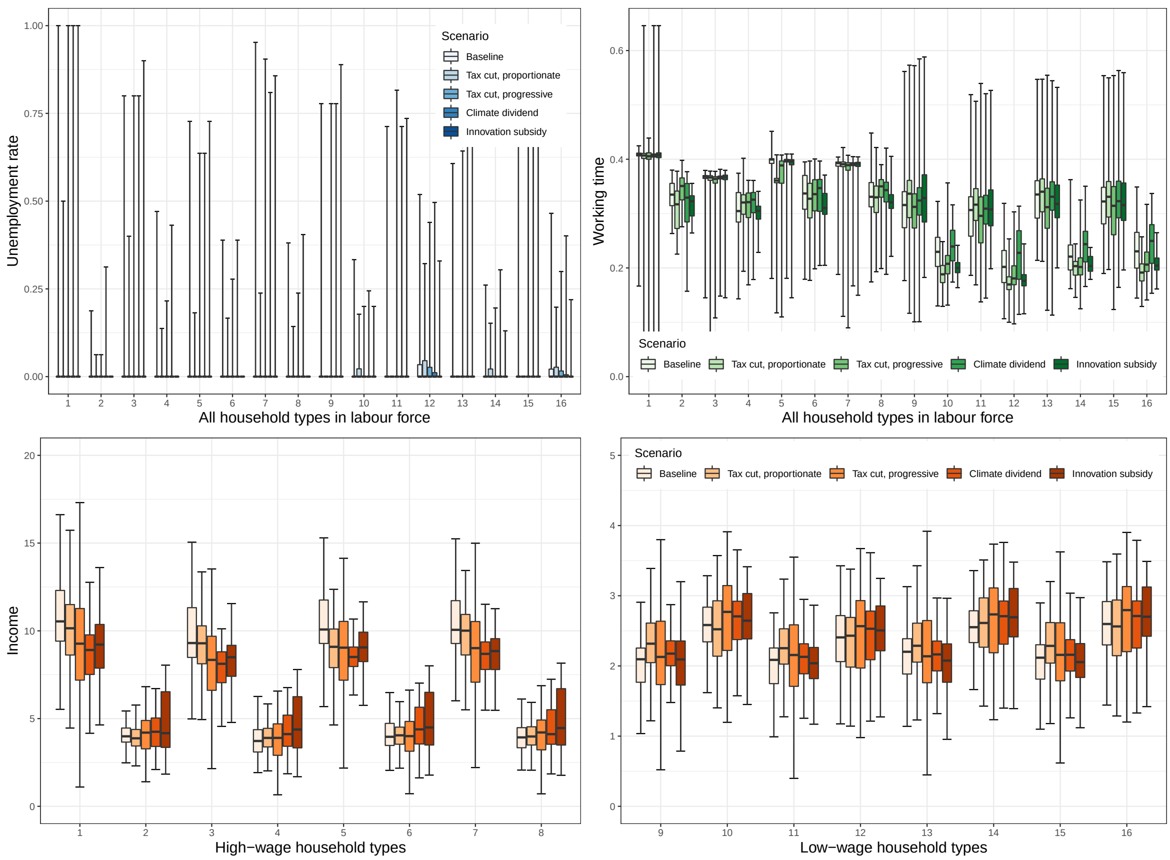


Figure 5.4: Unemployment, work time and income by household type and policy scenario

Note: Each box plot summarises unemployment, work time or income for one household type over all model rounds after the tax introduction.

[6]The income effects for individuals outside of the non-labour force are shown in Appendix 5.E.

High-wage earners (1-8) display very high employment rates with occasional upwards outliers, whereas low-wage workers (9-16), especially in the labour-intensive sector, S (even numbers) are facing somewhat more unemployment. In this group, unemployment is slightly higher under a proportionate tax cut. The longer whiskers show more volatility in employment in the energy-intensive sectors C and D (odd numbers), compared to sector S.

Proportionate income tax cuts seem particularly conducive to employment across most worker types, combining higher employment rates with work time reduction per person for many groups. The progressive income tax reduction also reduces unemployment for most groups.

Total energy consumption, i.e. from production and final use of the goods, falls in three out of four policy scenarios. Both income tax cuts and the innovation scenario achieve such an environmental dividend. When a climate dividend is paid, however, total energy use almost triples. This increase in energy use is driven by more energy use during consumption time for all goods, but good S in particular. Energy use during production falls across all policy scenarios, but it is not sufficient to counter the increase in energy consumption driven by income effects.

There is potential for a double dividend in all policy scenarios, except for the climate dividend. When tax revenues are used to reduce distortionary income taxes or when they are invested in energy-saving innovation, gains in employment and purchasing power can be observed. When a more equitable climate dividend is paid to each household an environmental dividend is not reached. Economic benefits, both in terms of PP and employment, are strongest in the innovation scenario. It is here, however, that we find some gender differences in the labour-intensive sector S, benefiting rural men in terms of purchasing power, and urban men in terms of employment.

Progressive income tax cuts produce the best results in terms of environmental improvement. They combine the strongest energy reductions in the production process with a shift in energy use during consumption time from good C to (mostly) good S. Both types of income tax reduction show trade-offs between PP and employment. Proportionate tax cuts are better at reducing unemployment, especially among high-wage earners. On the other hand, PP increases more under a progressive tax reduction. These gains benefit low-wage employees in particular, but come at the cost of high-wage workers in energy-intensive sectors, as well as the non-labour force.

Innovation

Innovation is not technically part of the double dividend, but can be important for the working of a carbon tax. Figure 5.5 shows the innovation strategies chosen by the three firms. Each firm can invest in product innovation, i.e. increasing the energy-efficiency of the good it produces (*Use energy*), or in process innovation, i.e. increasing the productivity of one of their factor inputs (*Production energy*, *Low-wage labour*, or *High-wage labour*). If a firm's profits are growing, it will not innovate at all, except when it receives subsidies to do so (innovation subsidy). The bar plots show the frequency with which each firm chooses a certain innovation strategy before the tax implementation (left of y-axis), and afterwards (to the right of the y-axis).

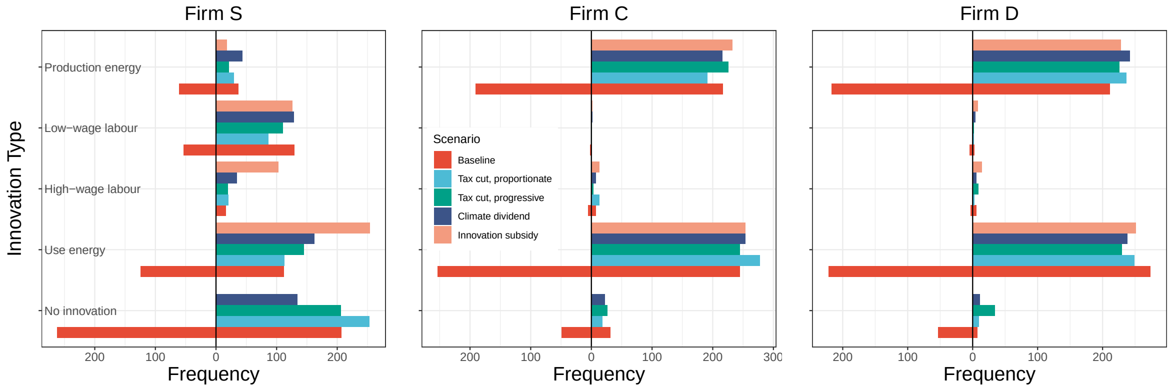


Figure 5.5: Innovation strategies

Note: Frequency of directing innovation towards energy or labour inputs, or towards use energy efficiency by firm. Y-axis marks policy introduction. Left of axis: before tax implementation; right of axis: after tax implementation

Before the tax reform, Firm S is overall less prone to innovate than Firms C and D. The latter two show few periods without any innovation effort. They both mostly try to improve energy efficiency of their production (Production energy) or of their final goods (Use energy). Their innovation strategies remain targeted towards energy in all scenarios after the tax implementation. Firm S on the other hand performs innovation less frequently, both before and after the tax. This makes sense, as the policy favours the less-energy intensive sector by nature. Whenever Firm S invests in innovation, it most frequently targets use energy, which is a mostly demand-driven innovation in our model.

The results of the firms' innovation efforts are displayed in Figure 5.6. The rows show the development of low-wage labour, high-wage labour, and energy technology in production, as well as energy-efficiency during consumption. There is no notable innovation in energy-efficiency during use for goods S and D, nor on low-wage labour productivity for firms C and D.

Under the proportionate income tax reduction, the production of S becomes more energy-efficient and high-wage labour productivity increases for Firm C. Progressive income tax cuts result in a particularly strong rise in high-wage labour productivity in sector S. The climate dividend does not seem to favour any particular type of technological progress. Innovation subsidies result in the clearest improvements for low-wage labour productivity in sector S, use energy of good C, as well as energy-efficiency in production across all three sectors.

5.4.2 Social interaction

The results presented above all take place in a setting with no social interaction. Next, we test the policy effects in an environment with socially-embedded preferences. In particular, each individual

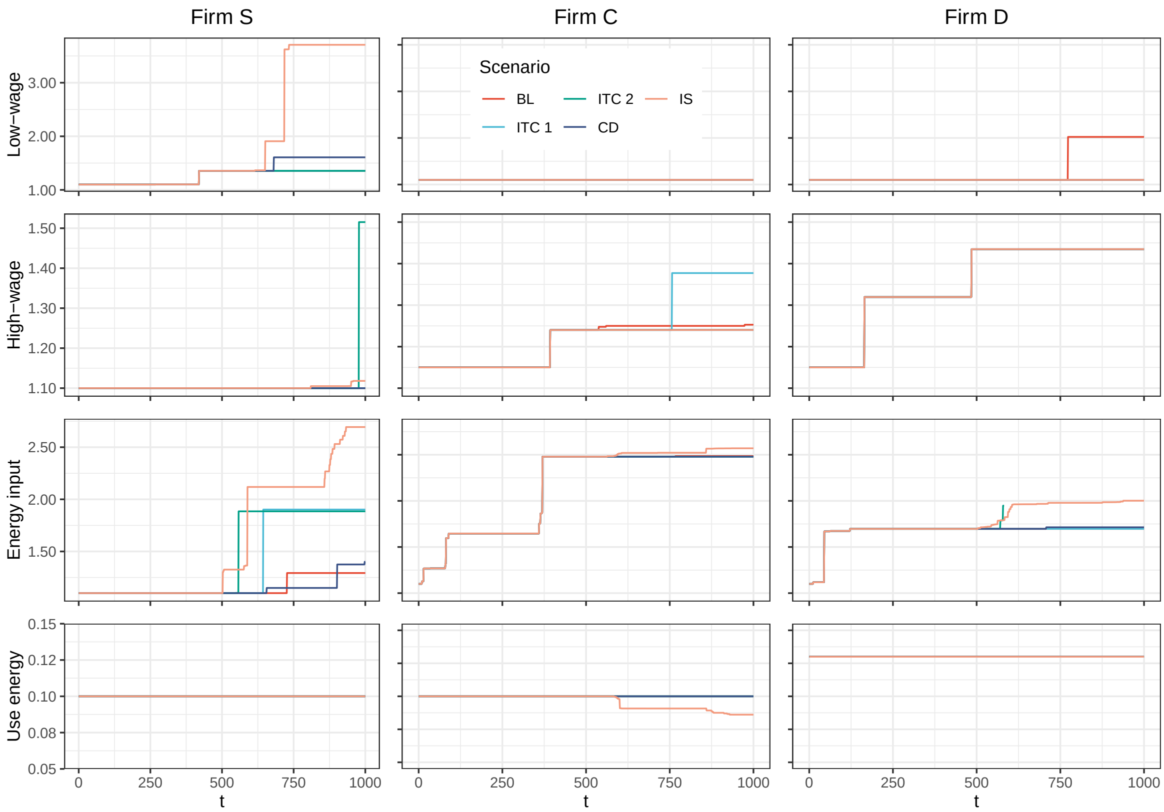


Figure 5.6: Innovation outcome

Note: BL: Baseline; ITC 1: Income tax cut, proportionate; ITC 2: Income tax cut, progressive; CD: Climate dividend; IS: Innovation subsidy.

observes peers who are equal in terms of gender, geographical location, and sector of employment, but who are high-wage earners and who have a higher income than themselves, should they be members of the high-wage group as well. Each household aspires to the average consumption habits of this peer group. Note that in this case, the wealthier a household is, the more influential their consumption patterns will be on their surroundings. This aspirational time use and consumption expenditure enters the household decision through the social multiplier (Konc et al., 2021) as described in Section 5.2. The expenditure share for good D tends to be higher among low-wage earners, while the reverse holds true for high-wage employees.

We can observe some relatively stable time use patterns across all policy scenarios when adding the social component to the model. Workers in the less energy-intensive sector S start at relatively low levels of work time in the social setting compared to the non-social model version, but over time evolve towards longer work longer hours than in the non-social setting. In the social setting, high-wage workers in particular show lower levels of consumption time for good S, and more consumption time for good D. Low-wage workers in sector S shift from relatively high consumption time for good C towards more working time. The reason is that their expenditure is dominated by subsistence consumption of D, i.e. fulfilling basic needs they cannot reduce. Thus, the only way for this group to imitate the higher consumption share of good C they observe in their wealthier peers, is to increase their labour supply.

It should be noted that we work with endogenous preferences in the social setting, because changes in peer behaviour actually alter households' preference parameters (see Section 5.2). Compensatory variation, however, only acts as a meaningful welfare measurement under the assumption of stable preferences. Since there is no simple alternative we report the changes in actual utility experienced by households for the social settings of our model and will focus mostly on employment effects for these cases.

Unemployment falls only in the climate dividend scenario and energy consumption decreases only when revenues are used to support investment in innovation. Innovation is more successful in improving energy-efficiency in the production of D in this model setting. Overall, we observe that the potential for an employment double dividend is much lower when households imitate each other compared to the non-social setting: We do not observe it in any of the four policy scenarios.

Again, we get a better picture of the distributional effects by looking at developments for different household types. Employment effects are broadly speaking more positive for low-wage types than for high-wage types. High-wage workers in sector S are especially vulnerable under income tax cuts. This is because the two high-wage labour markets (S vs. C/D) have a very different wage structure. The labour market with only one buyer (S) pays much lower wages than C and D, who compete for workers. The income tax cuts lead to a strong reduction in labour supply among the high-wage workers in sector S. The resulting shortage in labour supply drives up the high-wage rate in sector S and leads to substitution towards energy, a production factor which has become slightly more expensive through the tax, but also more efficient through innovation.

When income tax cuts are proportionate, the higher unemployment rates come with a strong rise in work hours per person. Labour demand of firm S is distributed across fewer workers. This further erodes the possibility of creating new jobs among high-wage workers. We do not observe the same patterns for low-wage workers, whose wage rates are more similar between the three firms.

The social setting seems to produce a sort of "work-and-spend" pattern in certain groups, where households work more in order to imitate their peers' consumption patterns. In high-wage sector S, the labour distribution becomes more polarised, with one share of households increasing their working hours and others becoming unemployed. This dynamic is detrimental to employment creation for the broader population. An unexpected but important result is that changes in wage dynamics can lead to shifts towards energy as a production factor in market S. The difference in S and C/D shows that this seems to depend on the initial labour market conditions.

Environment effects are especially negative under the income tax cuts, where most household types shift consumption away from good C, towards either S or D. The innovation subsidy is the only policy that considerably reduces energy use on both, production and consumption side. In all other scenarios energy use in production increases when households are imitating each other. This is in line with the observations of the previous paragraphs.

Figure 5.7 shows the average shares of consumption expenditure by good and household type for each policy scenario (Pol), compared to the baseline (BL). It shows that the consumption share of D is higher for most low-wage workers, compared to otherwise similar high-wage workers. Of the two less impactful consumption goods, sufficiency behaviours are more common among low-wage groups, whereas high-wage households spend a higher share of their income on the energy-efficient good C.

5.4.3 Green preferences and interacting agents

Section 5.4.2 showed that social interaction through imitation can erode the double dividend potential of a carbon tax, especially the environmental dividend. In Chapter 2, we suggested that status consumption might be linked to "green" behaviours as well, especially in segments of the population that have a higher preference for environmentally-friendly goods. We test this by introducing stronger preferences for non-materialistic (S) and energy-efficient consumption (C) to a share of the household population. Households are still social, but now they imitate only those peers who, in addition to a higher income, have the same preference structure (normal vs. green).

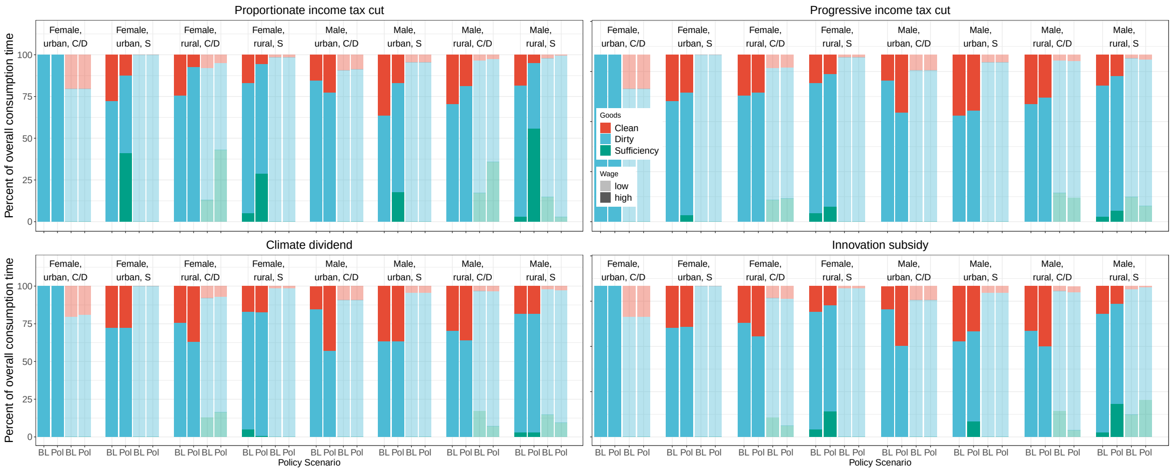


Figure 5.7: Expenditure share for each good by household type

Note: Darker colour represents the high-wage type, transparent colour the respective low-wage type.

We assign such intrinsic "green" preferences (a higher v_i) randomly. However, the likelihood of exhibiting green preferences is higher for household types, who reported a larger share of consumption of C and S in the ReZeitKon survey for Germany. The probability of a household to be green is defined as the common share of C and S behaviours in overall consumption[7]. Preferences are drawn at the beginning of the first model round and remain constant for each individual afterwards.

The probability for being green, according to the survey results, is highest for female urban workers in sector S (64.12%). Other households in the labour force who are likely to exhibit green preferences are male rural high-wage workers in sector S and female urban low-wage workers in the C/D sector. Interestingly, the high-wage type corresponding to the latter group (female, urban, high-wage, C/D) has the lowest probability of being green (33%). This means, one might expect positive environmental effects of imitation for some groups, but negative ones for other groups. In the non-labour force population we see a clear gender divide in participation in green behaviours, with women being more likely to behave pro-environmentally. We cannot distinguish, however, if this may be linked to differences in income.

Again, we focus on the employment double dividend, because agents' preferences are endogenous. The overall unemployment rate rises across all scenarios, so that this social setting with two different strengths of intrinsic green preferences does not show any double dividend potential under the current settings. It should be noted though, that this model setting shows the strongest environmental dividend potential (again with the exception of the climate dividend). Higher preferences for more time-intensive green consumption reduces labour supply and amounts produced. As some households still remain with the "normal" preferences, work time is not equally reduced

[7]See Table 5.1 for reported shares.

to distribute remaining work.

Under both income tax cuts unemployment rises stronger for high-wage households. It increases together with hours worked per person for almost all household types. Employment creation is undermined, as the tax cuts stimulate labour supply at the intensive margin. When the tax cut is progressive, we observe a relative shift in unemployment from low- to high-wage workers. Low-wage employment in sector S even rises. Under this policy, work time per person falls across almost all groups.

The innovation subsidy is shifting unemployment towards low-wage households, and low-wage employees in S in particular. These groups face higher unemployment combined with lower work hours per capita. At the same time, a per capita work time reduction combines with higher employment rates among high-wage employees in S. Firm S is successfully innovating on labour-efficiency in this model setting. Firm C also improves its high-wage labour efficiency more than in previous settings.

The climate dividend benefits the non-labour force above all. At the same time unemployment falls among low-wage workers in C/D and almost all low-wage types have reduced work hours.

5.4.4 Leisure preferences and independent agents

In the ReZeitKon survey, different household types state distinct wishes for additional leisure over a potential pay raise (see Table 5.1). The share of workers stating a preference for leisure is particularly high among high-wage urban female workers in S, followed by low-wage male service workers living in rural areas. More employees in the sufficiency (service) sector prefer a work time reduction compared to employees in the clean/dirty (industry) sector.

We run the model again with independent (non-social) households, but this time varying the preference parameters for consumption time. Household types who report a leisure preference more frequently in the German survey (Table 5.1), have a higher probability to receive a strong leisure preference in the model. A strong leisure preference means that these households obtain twice the utility from consumption time (u_c, u_d, u_s), relative to utility from ownership (o_c, u_d), than the rest of the population. Testing leisure preferences in the non-social setting allows us to compare the pure effect of this time preference, without any imitation effects.

When a share of the population has higher preferences for leisure/consumption time, the effects of an environmental tax reform on unemployment are qualitatively similar to the results we get when all households have equal lower leisure preferences (Section 5.4.1). With the exception of the climate dividend, all revenue recycling options lower the unemployment rate. However, the change rates are less pronounced under stronger leisure preferences. Contrary to the model setting without specific leisure preferences, the increase in employment goes along with a reduction in PP.

For progressive tax cuts and innovation subsidies this can be explained by a simultaneous work time reduction. Here we see an opposite effect to that in the previous subsections. A stronger preference for leisure distributes labour across a larger number of people.

The drop in PP also lowers energy use. Overall, energy use reductions are driven almost solely by reductions in energy during production in this model setting. We see barely any energy reduction on the consumption side. The reason is that consumption time is now more valuable relative to the amount of goods owned. This leads to a shift from production- to consumption-based energy use.

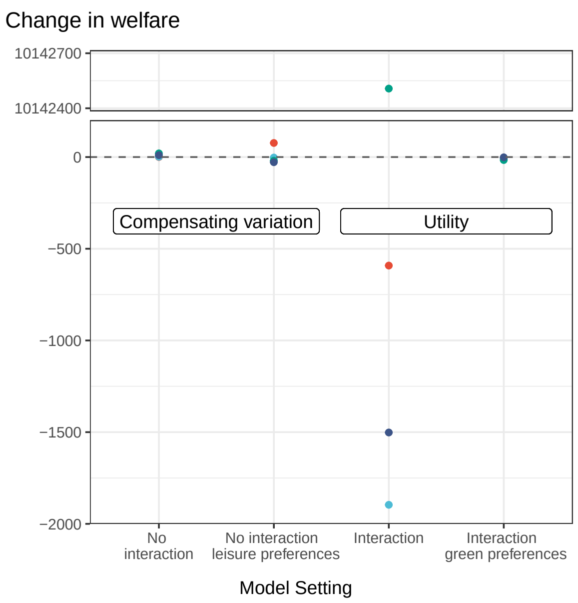
Figure 5.8 gives an overview of the main outcomes by model setting and policy scenario (see Appendix 5.7 for exact values). For an economic dividend, the direction of change should be positive for welfare (point above horizontal line in sub-figure A) or negative for unemployment (point below horizontal line in sub-figure B). An environmental dividend is reached when energy use falls (point below horizontal line in sub-figure C).

5.5 Conclusions

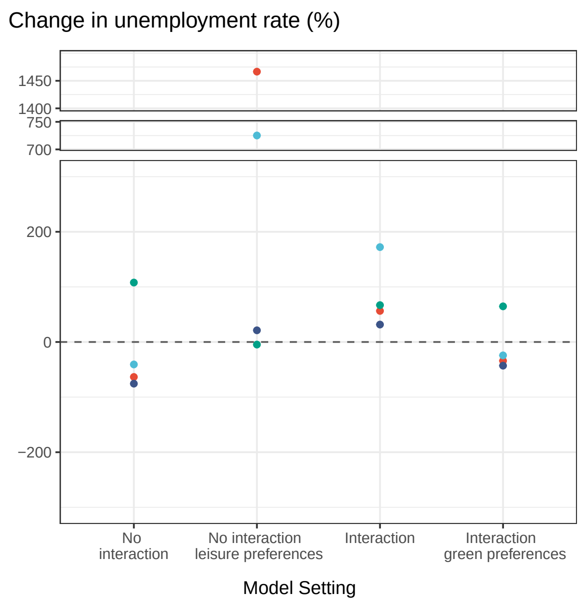
We built an agent-based model for environmental tax reforms inspired by the beha-vioural-evolutionary concepts of routines, and social interaction, adopting an activity-based perspective. This means our three goods: dirty, clean and sufficiency represent lifestyles, or activities, rather than merely objects. Households are heterogeneous with respect to education, employment sector and labour participation, gender and geographical area. All agents are satisficers, optimizing under imperfect information and only when triggered by their environment to do so. A trade-off between paid labour and consumption time under the constraint of unpaid labour time is introduced. Polluting energy is needed for production and consumption of goods.

We apply this ABM to study the effects of a revenue-neutral environmental tax reform for four different revenue-use scenarios: (1) proportionate income tax cuts, (2) progressive income tax cuts, (3) a per capita climate dividend, and (4) earmarking for energy-saving innovation. The outcomes we focus on are purchasing power, employment, energy consumption and to some extent innovation. Since in the social settings of our model household preferences are endogenous, we neglect purchasing power in this case and focus on the employment double dividend.

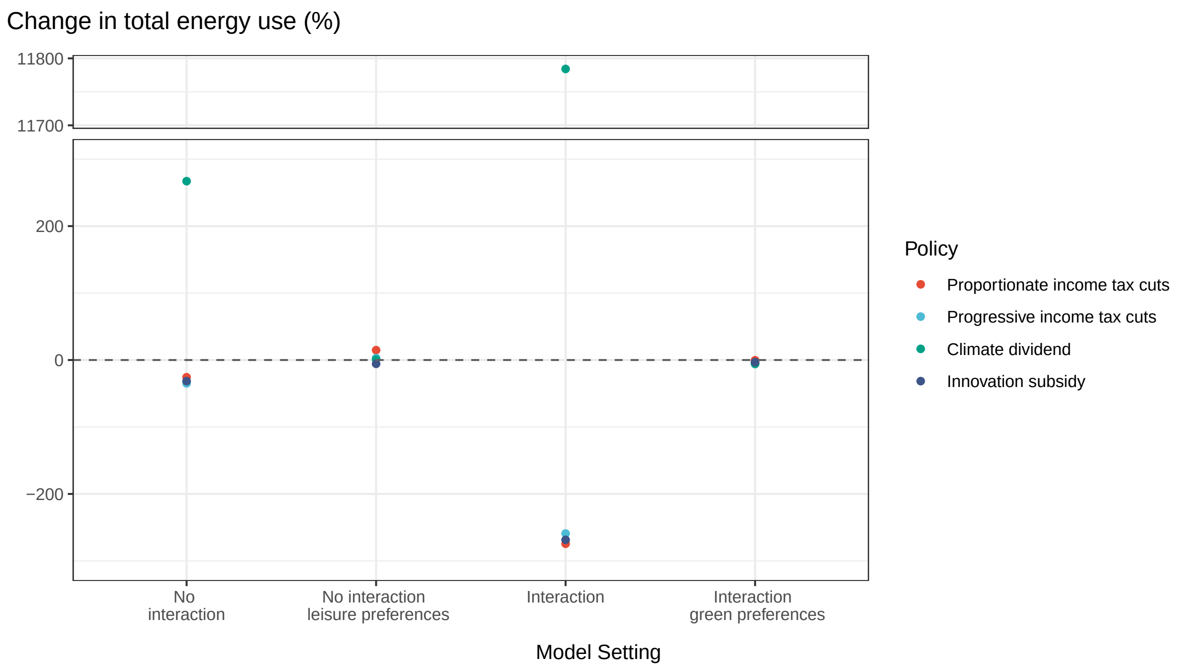
The model version in which households make choices independent of each other (non-social or independent above) appears most conducive to a double dividend, as well as to an employment double dividend. An exception is the case where revenues are used to pay out a per capita climate dividend. We find that all policy scenarios yielding a double dividend take away purchasing power from people outside the workforce. Overall, we see a distribution away from high-wage workers



(a) Economic dividend



(b) Employment dividend



(c) Environmental dividend

Figure 5.8: Main policy outcomes by model setting and scenario

Note: Changes under various revenue-recycling options compared to the baseline (no policy) in percentage points. Welfare measured in compensating variation for independent agents and in utility changes for socially-interacting agents. Tax rate, $\tau_E = 10\%$. Note that some of the positive effects are particularly high, when starting from very low initial values. Based on an individual model runs.

in the C/D sector, in favour of their counterparts in sector S. Gains in purchasing power can be highly gendered for high-wage rural workers in sector S, because of gender gaps in binding care work. Energy use in production falls across all scenarios.

In a social setting, where households aspire consumption patterns of more affluent peers, we observe an increase in work time and shift towards time-saving, but energy-intensive consumption for certain groups. Very broadly speaking, in this scenario we see the policies drive up unemployment. Higher average work time erodes potential employment creation and the wage dynamics in the high-wage labour market for firm S lead to a shift towards energy use in production. In fact, energy use rises in almost all scenarios. Thus, chances for a double dividend are much lower with social agents and the environmental dividend depends on innovation subsidies. We observe no employment double dividend.

When a share of these interacting households exhibits stronger green preferences, the chances for a strong environmental dividend increase. At the same time, however, the outlook is bleak for an employment dividend. Indeed, we see no EDD under any policy scenario here, either. All scenarios show increased unemployment, combined with longer work hours. Workers who get matched for a job work longer, fulfilling labour demand with fewer heads.

Adding different leisure preferences to the independent (non-interacting) model setting through increasing the relative value of consumption time shows similar potential for an employment double dividend as the case with equal leisure preferences. While there are little to no reductions in energy use during consumption, reductions in energy use for production ensure an environmental dividend. The reason is that utility depends more on consumption time than on the amount of goods consumed in this setting. This, in turn, means households lower their work time in favour of consumption time, leading to a broader distribution of work among the whole population.

The model settings without interaction (imitation) yield better outcomes in terms of the double dividend. In the basic non-social setting the economic dividend tends to materialise through higher purchasing power and increased employment. The non-social setting with stronger leisure preferences, on the other hand, mostly fosters an employment double dividend. Imitation of wealthier households inhibits the environmental dividend in particular, but it can also harm employment creation when work time per capita increases. When social interaction is combined with green preferences, we observe some of the strongest environmental dividend. However, never in combination with an economic dividend.

Apart from assessing the DD potential of different policy designs, our study has revealed highly heterogeneous impacts across the agent population. Policy makers therefore not only face trade-offs between the economy and the environment but also between different segments of the population. It is of course a political question, which trade-offs ought to be made. However, education, sector of employment, gender and geographical location have all proven relevant characteristics in terms of policy impact and we strongly advocate for integrating such characteristics more systematically in economic studies of environmental tax reforms.

We want to mention a few important limitations of our approach. Conceptually, one could disagree on the definition of our three representative goods. However, these already go beyond the simple and arguably less realistic distinction between clean and dirty goods as adopted in most theoretical models of ETR. Another challenge that is common to simulation models concerns parametrisation. Behavioural parameters in particular are difficult to estimate. We endeavoured to base our choices on empirical observations. The ReZeitKon survey (Geiger et al., 2022), unique in its combination of variables about time use and consumption behaviours, was indispensable in this regard.

We have demonstrated a number of policy experiments. However, these have by no means exhausted the capabilities of our agent-based model. Its flexibility provides a comprehensive basis for further research into policy designs or behavioural assumptions. We hope that this study can inspire a broader modelling approach to environmental taxation. Grounding different research questions and policy options in one flexible model framework has forced us in any case to consider a broad set of climate policy impacts. This has highlighted many potential policy costs and benefits and their multi-dimensional distribution. We hope this ultimately will contribute to better climate policy design.

References

Aubert, D. and Chiroleu-Assouline, M. (2019). Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82.

Carattini, S., Carvalho, M., and Fankhauser, S. (2018). Overcoming public resistance to carbon taxes. *Wiley Interdisciplinary Reviews: Climate Change*, 9(5):e531.

Douenne, T. and Fabre, A. (2020). French attitudes on climate change, carbon taxation and other climate policies. *Ecological Economics*, 169:106496.

Edenhofer, O., Flachsland, C., Kalkuhl, M., Knopf, B., and Pahle, M. (2019). Options for a carbon pricing reform. *Mercator Research Institute on Global Commons and Climate Change (MCC): Berlin, Germany*, pages 1–9.

Foramitti, J. (2021). Agentpy: A package for agent-based modeling in python. *Journal of Open Source Software*, 6(62):3065.

Geiger, S. M., Gerold, S., Günther, A., von Jorck, G., and Schrader, U. (2022). Repräsentativerhebung projekt ReZeitKon - Zeit-Rebound, Zeitwohlstand und nachhaltiger Konsum. Retrieved from osf.io/j3he5.

Goulder, L. H. (1995). Environmental taxation and the double dividend: a reader's guide. *International tax and public finance*, 2(2):157–183.

Havranek, T., Irsova, Z., Laslopova, L., and Zeynalova, O. (2020). The elasticity of substitution between skilled and unskilled labor: A meta-analysis. *University Library of Munich*, MPRA Paper no. 102598. URL: https://mpra.ub.uni-muenchen.de/id/eprint/102598

Klein, F. and van den Bergh, J. (2021). The employment double dividend of environmental tax reforms: exploring the role of agent behaviour and social interaction. *Journal of Environmental Economics and Policy*, 10(2):189–213.

Konc, T., Savin, I., and van den Bergh, J. C. (2021). The social multiplier of environmental policy: Application to carbon taxation. *Journal of Environmental Economics and Management*, 105:102396.

Koschel, H. (2000). Substitution elasticities between capital, labour, material, electricity and fossil fuels in German producing and service sectors. *ZEW discussion paper*, No.00-31.

Maestre-Andrés, S., Drews, S., Savin, I., and van den Bergh, J. (2021). Carbon tax acceptability with information provision and mixed revenue uses. *Nature Communications*, 12(1):1–10.

Pearce, D. (1991). The role of carbon taxes in adjusting to global warming. *The economic journal*, 101(407):938–948.

Repetto, R. and Dower, R. C. (1992). Reconciling economic and environmental goals. *Issues in Science and Technology*, 9(2):28–32.

Van der Werf, E. (2008). Production functions for climate policy modeling: An empirical analysis. *Energy economics*, 30(6):2964–2979.

Welsch, H. and Ochsen, C. (2005). The determinants of aggregate energy use in west germany: factor substitution, technological change, and trade. *Energy Economics*, 27(1):93–111.

Appendix 5.A The household problem

When households optimise their consumption, they do so on six variables: the amounts of three types of consumption goods bought beyond subsistence consumption, as well as the time spent using them, respectively. Maximising the household utility function with respect to the time constraint and the budget constraint thus yields the following six first order conditions:

$$\frac{1}{\sigma}(...)^{\frac{1}{\sigma}-1}\alpha(t_S u_S)^\sigma S^{\sigma-1} = \lambda\left[p_S + (1+\tau_{E,t})p_E t_S e_S\right] \tag{5.14}$$

$$(...)^{\frac{1}{\sigma}-1}\frac{1-\alpha}{\delta}[...]^{\frac{\sigma}{\delta}-1}\epsilon\delta(t_C u_C + o_C)^\delta C^{\delta-1} = \lambda\left[p_C + (1+\tau_{E,t})p_E t_C e_C\right] \tag{5.15}$$

$$(...)^{\frac{1}{\sigma}-1}\frac{1-\alpha}{\delta}[...]^{\frac{\sigma}{\delta}-1}(1-\epsilon)\delta(t_D u_D + o_D)^\delta (D-\bar{D})^{\delta-1} = \lambda\left[p_D + (1+\tau_{E,t})p_E t_D e_D\right] \tag{5.16}$$

$$\frac{1}{\sigma}(...)^{\frac{1}{\sigma}-1}\alpha(u_S S)^\sigma t_S^{\sigma-1} = \lambda\left[(1-\tau_{i,t})w_{i,t} + (1+\tau_{E,t})p_E e_S S\right] \tag{5.17}$$

$$(...)^{\frac{1}{\sigma}-1}\frac{1-\alpha}{\delta}[...]^{\frac{\sigma}{\delta}-1}\epsilon\delta(t_C u_C + o_C)^{\delta-1} C^{\delta} = \lambda\left[(1-\tau_{i,t})w_{i,t} + (1+\tau_{E,t})p_E e_C C\right] \tag{5.18}$$

$$(...)^{\frac{1}{\sigma}-1}\frac{1-\alpha}{\delta}[...]^{\frac{\sigma}{\delta}-1}(1-\epsilon)\delta(t_D u_D + o_D)^{\delta-1}(D-\bar{D})^{\delta} = \lambda\left[(1-\tau_{i,t})w_{i,t} + (1+\tau_{E,t})p_E e_D(D-\bar{D})\right] \tag{5.19}$$

where

$(...) = \alpha(t_S u_S S)^\sigma + (1-\alpha)\left[\epsilon((t_C u_C + o_C)C)^\delta + (1-\epsilon)((t_D u_D + o_D)(D-\bar{D}))^\delta\right]$

and

$[...] = \epsilon((t_C u_C + o_C)C)^\delta + (1-\epsilon)((t_D u_D + o_D)(D - \bar{D}))^\delta.$

Appendix 5.B The firm problem

The firms are maximizing their respective profit functions with respect to the numbers of vacancies posted, $v_{L,j,t}$ and $v_{H,j,t}$, and the energy input. They maximise expected profits, defined as:

$$\Pi^{exp}_{j,t} = p_j y_{j,t} - CH_S - CL_S - w_{L,n,j,t}L_{j,t} - w_{H,n,j,t}H_{j,t} - c_L v_{L,j,t} - c_H v_{H,j,t} - (1+\tau_{E,t})p_E E_{j,t} \quad (5.20)$$

The total amount of labour hours depends on the existing labour stock, working time of each employee and successful new matches. The firms thus approximate their expected realised labour inputs as the sum of their existing stock of labour and newly formed jobs. The total realised labour inputs are then defined as:

$$L_{j,t} = L_{s,j,t} + L_{n,j,t} = L_{s,j,t} + \bar{t}_{w,L} q_{L,j,t} v_{L,j,t} \quad (5.21)$$

$$H_{j,t} = H_{s,j,t} + H_{n,j,t} = H_{s,j,t} + \bar{t}_{w,H} q_{H,j,t} v_{H,j,t} \quad (5.22)$$

where the new labour $L_{n,j,t}$ and $H_{n,j,t}$ are the product of average work time among the existing workforce ($\bar{t}_{w,L}$ and $\bar{t}_{w,H}$), the number of vacancies posted ($v_{L,j,t}$ and $v_{H,j,t}$) and the probability of a vacancy to turn into a job ($q_{L,j,t}$ and $q_{H,j,t}$).

The matching probabilities reflect the number of new jobs created per vacancy posted in the previous period:

$$q_{i,j,t} = \frac{j_{i,j,t-1}}{v_{i,n,j,t-1}} \quad (5.23)$$

When we substitute these equations into the production function, the output in period t, $y_{j,t}$, is defined as[8]:

$$y = [s_L(A_L(L_s + \bar{t}_L q_L v_L))^\rho + s_H(A_H(H_s + \bar{t}_H q_H v_H))^\rho + s_E(A_E E)^\rho]^{\frac{1}{\rho}} \quad (5.24)$$

The three first-order conditions for a profit maximum become:

$$p_j\,[...]^{\frac{1}{\rho}-1}\, s_L A_L^\rho (L_s + \bar{t}_{L,j} q_L v_L)^{\rho-1} \bar{t}_{L,j} q_L = c_L + w_{L,t}\bar{t}_{L,j} q_L \quad (5.25)$$

$$p_j\,[...]^{\frac{1}{\rho}-1}\, s_H A_H^\rho (H_s + \bar{t}_{H,j} q_H v_H)^{\rho-1} \bar{t}_{H,j} q_H = c_H + w_{H,t}\bar{t}_{H,j} q_H \quad (5.26)$$

[8] For more readability, the indices t, i and j are dropped in this equation.

$$p_j\,[...]^{\frac{1}{\rho}-1}\,s_E A_E^{\rho} E^{\rho-1} = (1+\tau_{E,t})p_E \tag{5.27}$$

where

$[...] = s_L(A_L(L_s + \bar{t}_{L,j}q_L v_L)^{\rho} + s_H(A_H(H_s + \bar{t}_{H,j}q_H v_H))^{\rho} + s_E(A_E E)^{\rho}$

The marginal products of labour are equal to the marginal price of the respective labour type, which includes wage costs and hiring costs. The marginal price of energy is reflected by the energy price and a potential pollution tax.

Appendix 5.C Consumption behaviours

We categorise the consumption behaviours according to the major categories mobility, food, housing and other. For each we assign certain responses about frequencies of behaviours, or whether they are performed at all to our three consumption good categories.

Table 5.4: Classification of consumption behaviours

	Mobility	**Food**	**Housing**	**Other**
Dirty	Use of diesel/petrol car and plane; yearly vacation by plane (4-5)	Main meals: meat (4-5); food waste (2-5)	High p.c. surface; heating (3-5)	Buy what I need, eco labels, energy-efficient appliances and repair (1-3), second hand and borrow/lend(1-2), clothes and electronics: high
Clean	Use of electric/gas car and motorcycle; yearly vacation by plane (3)	Main meals: meat (2-3); food waste (2-5); organic food (4-5)	*Ökostrom*; heating (3-5)	Buy what I need and repair (1-3), eco labels and energy-efficient appliances (4-5), second hand and borrow/lend(3), clothes and electronics: high
Sufficient	Walking, biking, public transport; yearly vacation by plane (1-2)	Main meals: meat (1); food waste (1)	low p.c. surface; flat share, heating (1-2)	Buy what I need, repair, second hand and borrow/lend (4-5), clothes and electronics: low

Note: Numbers represent responses on a 5-point rating scale about how frequent a behaviour is performed, where 1=never, 2=seldom, 3=occasionally, 4=often, 5=always.

Appendix 5.D Cost shares

Another study that provides an overview of cost shares by industry for Germany is Koschel (2000). We present here a table with their values matching our categorisation of the household survey data. Some categories show wide variation in cost shares. For these we add in parentheses the averages provided in the same paper.

Table 5.5: Energy and labour cost shares by sector

	Sector	**Fossil energy**	**Electricity**	**All energy**	**Labour**
C & D	*Industry/manufacturing*	0.2-48.0	0.6-6.8	0.8-54.8 (11.85**)	3.4-43.4 (88.16**)
	Construction	1.1	0.1	1.2 (3.17)	36.6 (96.83)
	Transport/logistics	1.7-8.7	0.2-4.8	1.9-13.5 (22.45*)	18.7-35.6 (77.55*)
Sufficiency	Trade	1.7-1.8	2.9-4.8	4.6-6.6 (28.41*)	4.7-11.7 (71.59*)
	Hotels/catering	0.9	2.5	3.4 (12.45)	23.9 (87.54)
	Financial services/insurance	0.2-0.3	0.6-0.7	0.8-1.0 (2.34*)	29.2-48.5 (97.66*)
	Research/education	0.6	0.8	1.4 (4.42)	30.3 (95.58)
	Health/social sector	0.5	0.3	0.8 (2.68)	29.0 (97.32)
	ICT	0.5	0.7	1.2 (3.15)	36.9 (96.85)

Note: Relative cost share only regarding energy and labour in parentheses (in percent). (*) For financial services/insurance, trade and transport we calculated the category average. (**)Industry and production value is mean of energy and non-energy intensive manufacturing category taken from the source article (Koschel, 2000).

Most of what we classified as "sufficiency" sectors has a relatively low cost share of energy, with the exception of trade and hotels/catering. However, these are both driven by electricity use, which can be more easily decarbonised[9]. So the reliance on fossil energy is relatively low. As expected, transport/logistics, industry and production show higher energy cost shares. Construction, which we also classified as high-energy low-labour, however, has a very low energy cost share. We argue here that it has little primary energy use, but high fossil energy use embedded in its supply chain, thus in fact significantly relying on fossil fuels.

If we take into account only industry/manufacturing and transport/logistics for C/D, we get an energy share of 17.15% for this category (labour share 82.85%). This is leaning towards a slightly higher energy use, compared to Welsch and Ochsen (2005), who only included production, but it is the same order of magnitude. See Table 5.2 for the rounded final values. For S, adjusting trade and hotels/catering to fossil energy use, we get an average energy cost share of 4.22% (labour share 95.78%). We are rounding these values to the next 5 and divide the labour inputs to low- and high-wage labour with factors 2/3 and 1/3, respectively (based on the shares observed in production by

[9] Without electricity, the energy cost share for trade drops to 8.95%, for hotels/catering it falls to 3.77%.

(Welsch and Ochsen, 2005): If we also assume here that production is based only on energy and labour inputs, the shares of low- and high-wage labour are 57.79% and 28.57%). The data from Welsch and Ochsen (2005) are rather old, but the factor shares seem relatively constant over the 18 year period they look at.

Appendix 5.E Income of non-labour force by household type and policy scenario

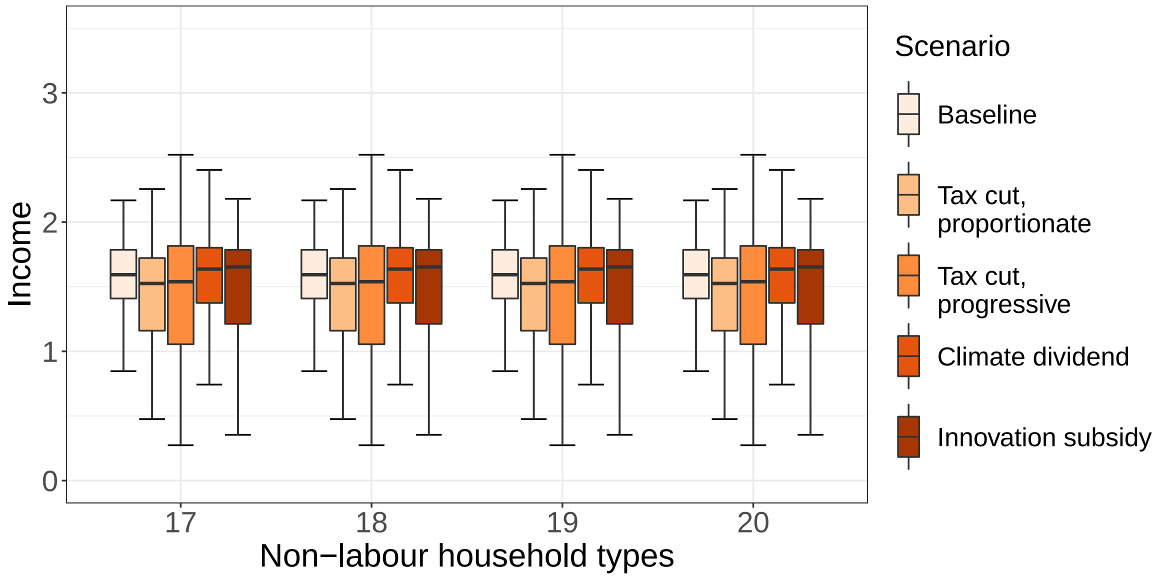


Figure 5.9: Income of population outside the labour force

Appendix 5.F Parameter values

Table 5.6: Model parameters

	Symbol	Description	Value
Fixed	ξ	Elasticity of matching function	0.5
	ω	Matching parameter	0.9
	β	Workers' bargaining power	0.5
	σ	Preference parameter (no-social)	0.5
	δ	Preference parameter (no-social)	0.5
	p_S	Price of good S	1
	p_C	Price of good C	1
	p_D	Price of good D	1
	p_E	Price of energy	1.5
	X	Wage adjustment rate	0.01
	R	Replacement rate	0.3
	F	Firing rate	0.02
	N_{HH}	Number of households	1575
	N_J	Number of firms	3
	u_S	Utility from time spent on S	2
	u_C, u_D	Utility from time spent on C or D	1
	o_C, o_D	Utility from ownership of C or D	0.1
	P_j	Productivity factors of firm j	20
	A_H, A_L, A_E	Technology factors of high-wage, low-wage labour and energy	1.1
	ι	Likelihood of success for innovation	0.8
	ρ	Production coefficient	-0.43
	c	Vacancy cost	0.02
Scenario-dependent	γ	Redistribution parameter	0 or 0.5
	τ_E	Carbon tax rate	10%
	$1-\alpha$	Material preference (no-social)	0.5
	ϵ	Environmental preference (no-social)	0.5
	ζ	Strength of social influence	0.25
	v_α	Personal preference for C/D over S	1/3 - 1/2
	v_ϵ	Personal preference for C over D	1/3 - 1/2

Note: Scenario-dependent parameters may vary with policy scenarios. Please note that several production parameter values are already defined in Table 5.5.

Appendix 5.G Main policy outcomes in table form

Table 5.7: Main policy outcomes by model setting and scenario

Model setting	**Policy**	**Compensa-ting variation/ Utility**	**Unemploy-ment rate**	**Total energy consumption**	**DD**
Independent	Proportionate ITC	0.28	-63.47	-25.68	yes
	Progressive ITC	1.75	-40.75	-34.81	yes
	Climate dividend	20.07	107.87	267.12	no
	Innovation subsidy	10.17	-75.59	-31.45	yes
Social interaction	Proportionate ITC	76.77	1466.62	14.76	no
	Progressive ITC	-2.62	725.25	2.92	no
	Climate dividend	-19.92	-4.68	0.69	no
	Innovation subsidy	-28.17	21.21	-5.67	no
Social interaction with green preferences	Proportionate ITC	-591,69	56.40	-274.43	no
	Progressive ITC	-1896.21	172.19	-259.08	no
	Climate dividend	10142507.29	66.92	11784.17	no
	Innovation subsidy	-1501.84	31.65	-268.57	no
Independent, stronger leisure preferences	Proportionate ITC	-5.04	-34.17	-0.29	yes
	Progressive ITC	-7.25	-24.27	-4.56	yes
	Climate dividend	-16.29	64.68	-5.92	no
	Innovation subsidy	-1.41	-42.97	-3.11	yes

Note: ITC = income tax cut; DD = double dividend. Changes under various revenue-recycling options compared to the baseline (no policy) in percentage points. Welfare measured in compensating variation for independent agents and in utility changes for socially-interacting agents. Tax rate, $\tau_E = 10\%$. Note that some of the positive effects are particularly high, when starting from very low initial values.

Chapter 6

Conclusions

This thesis has explored the potential for an employment double dividend using a behavioural-evolutionary modelling approach as an alternative to the traditional rational-agent equilibrium approach. Relevant behaviours and dimensions of heterogeneity were identified through a broad literature review (Chapter 2). A novel assumption of time use was investigated empirically (Chapter 3), and an explicit connection to and comparison of agent-based modelling with existing equilibrium analysis was established (Chapter 4). Finally, a comprehensive behavioural, agent-based model was developed to investigate ETR in a population of heterogeneous, socially-interacting agents (Chapter 5). Here we summarise the main insights obtained and suggest some ideas for further research.

Summary

Chapter 2 examined which particular deviations in behaviour from rational representative agents may affect the mechanisms and outcomes of an environmental tax reform. It reports a synthetic literature review, combining insights from various fields into working hypotheses for an agent-based model. While the results highlight many potentially relevant factors, I focus hereafter mostly on the most significant ones. Existing models lack attention for heterogeneity on the household side. This concerns especially labour supply decisions and the trade-off between work time and necessary consumption time. On the firm side, I considered the role of energy use in production, including variation between sectors, to the study of an *employment* DD. This allows to investigate innovation dynamics and structural transition potential. Our review further highlights the empirical relevance of habitual behaviour and social interaction. In particular, imitation of wealthier households is expected to influence an employment double dividend through labour and goods markets.

Chapter 3 presented an empirical investigation of the relationship between work time, leisure activities and resulting energy use for different types of employees, with applications to two countries, namely France and Finland. It differentiated between part-time and full-time employees and used distinct energy intensities for different activities by household type. In addition, we tested the nature and non-linearity of relationships between work time and the allocation of other activities. We found that the combination of work and leisure activities differs between the two countries, with variations between part-time and full-time workers being more pronounced in France than in Finland. This highlights the relevance of cultural and institutional context. Both countries exhibit significant non-linear links betweens work and certain activities. The application of two energy use metrics (total energy versus direct energy) revealed the importance of integrating energy use in both, production and consumption, into our final model.

Chapter 4 addressed challenge of developing a behavioural, agent-based model that closely resembles and can replicate the results of, a rational-agent general equilibrium model. To this end I studied the methodological translation from a GEM to an ABM, known as *agentization*. Taking a study by Aubert and Chiroleu-Assouline (2019) as a starting point, we find that most of their propositions are robust in that they hold up under our agent-based version. However, results relying on precise equilibrium conditions are hard to reproduce with an ABM. The agentization process stimulated a discussion of the role of monetary flows, such as potential profits, which are left out of consideration when developing an equilibrium model. We derive additional lessons from this study about agentization of GE models in general.

Next, Chapter 5 extended the model of Chapter 4 to arrive at a comprehensive ABM, adequate to study distinct aspects of environmental tax reform. Households are heterogeneous in terms of education (skills), gender, location, and status and sector of employment. They consume goods which exhibit distinct energy-efficiency and consumption time requirements, and which are produced with varying energy- and labour-intensity. Households and firms act habitually. Without social interaction and uniformly distributed preferences, the results of our model are in line with expectations from the previous literature. We find that progressive income tax reductions favour low-wage households more than proportionate income tax reductions. In addition, a per capita climate dividend paid to all households turns out particularly beneficial for purchasing power of individuals who are outside of the workforce, but it does not enable reductions in energy consumption. Innovation subsidies perform well in economic and environmental terms. A novel insight that the model reveals is that a tax reform may benefit men's employment in the high-wage rural service sector and men's purchasing power in the high-wage urban service sector disproportionately, compared to women in the same category.

We further find that stronger leisure preferences in a non-social setting yield qualitatively similar results for an employment double dividend as lower leisure preferences. An exception is the climate dividend, where environmental improvement can be seen only when leisure preferences are strong.

However, while the setting with low leisure preferences shows improvement in employment and purchasing power, the reduction in unemployment under stronger leisure preferences comes with lower purchasing power.

Another finding is that the imitation of wealthier peers reduces the potential for an employment double dividend, because it leads to an increase in average work time rather than job creation. Conforming with higher-status peers often leads to increased labour supply and consumption. A subsistence level of polluting consumption prohibits a flexible shift between goods and promotes additional labour supply and consumption. Furthermore, we find that in a social setting, wage dynamics can in fact lead to less labour and more energy use in production. This is the case for high-wage workers in the non-competitive service sector. Higher prevalence of green preferences in a social setting raises the chances for an environmental dividend but not for an employment dividend.

Our findings confirm many results of equilibrium model studies of the DD, indicating they are robust to different settings. Yet, taking a time-based perspective with multi-dimensional heterogeneity delivers a number of novel insights. Especially gendered patterns of consumption and labour supply have not received much attention in the study of the DD. Policy impacts do not clearly adhere to one dimension of heterogeneity, but we find that often the interaction of certain household characteristics is relevant, e.g. being a woman who lives in a rural area and works in a particular sector, rather than just gender as such. We also note complex interactions between wage dynamics and innovation that can hamper original intentions of the policy. Ignoring such interactions in economic models leads to ill-informed policy decisions. More attention for heterogeneity beyond income, such as in decision-making processes regarding labour supply and consumption, could greatly advance policy advise about environmental tax reforms.

Further research

Going beyond standard assumptions about economic agents, especially on the household side, has delivered many useful insights. But there are other interesting factors worth studying, especially regarding firm behaviour. This includes the role of firm size, firm extinction or social innovation in the reaction to an environmental tax reform. We discussed this briefly in Chapter 2. Integrating time requirements beyond labour supply, specifically consumption time and unpaid work, could be a great starting point for studying rebound effects in more detail. However, time use data is still relatively sparse and connecting it to energy consumption is difficult. Hence, more empirical research on activities and their energy intensity in a time series manner would be desirable.

We hope that this thesis can inspire further research into more complex approaches to environmental taxation. The results are interesting, at times surprising, and force us to challenge our way of thinking about environmental tax reforms.

References

Aubert, D. and Chiroleu-Assouline, M. (2019). Environmental tax reform and income distribution with imperfect heterogeneous labour markets. *European Economic Review*, 116:60–82.