Ecological Economics 217 (2024) 108070

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

How carbon pricing affects multiple human needs: An agent-based model analysis

Joël Foramitti [a,b], Ivan Savin [c,a,d,*], Jeroen C.J.M. van den Bergh [a,b,e,f]

[a] Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Spain
[b] Institute for Environmental Studies, Vrije Universiteit Amsterdam, The Netherlands
[c] ESCP Business School, Madrid Campus, Spain
[d] Graduate School of Economics and Management, Ural Federal University, Yekaterinburg, Russian Federation
[e] ICREA, Barcelona, Spain
[f] School of Business and Economics, Vrije Universiteit Amsterdam, The Netherlands

ARTICLE INFO

Keywords:
Climate policy
Human needs
Low-carbon infrastructure
Transport
Well-being

ABSTRACT

Climate policy is urgently needed to reduce emissions, but must also be evaluated in regard to its impact on human quality of life. To identify policy approaches that are able to achieve effective mitigation together with high levels of well-being, multiple human needs must be taken into account. To this end, we present an agent-based model that is able to describe the interaction between various economic sectors on the supply-side and individuals with heterogeneous incomes and needs on the demand-side. Individuals make choices under both income and time constraints; the latter being needed for non-market activities and time-intensive forms of consumption such as low-carbon modes of transport. The following climate policy instruments are considered: a carbon tax, permit trading, direct regulation, and investments in low-carbon infrastructure. Impacts are analyzed in regard to three different types of mitigation: avoid, shift, and improve. Results show that to achieve emission reductions together with high levels of well-being, carbon pricing is best combined with effective improvements of low-carbon infrastructure; revenue recycling should be progressive; and unnecessary abatement costs should be avoided. A comparison is provided with traditional formulations of social welfare.

1. Introduction

A central question of climate action is how emission reduction can be combined with a high quality of life for all people (O'Neill et al., 2018). On one hand, this depends on the economy's emission intensity, which describes the amount of consumption that can be realized per unit of emission. However, not all consumption is of equal importance to human well-being (Gough, 2017). Thus, it also matters which goods and services are produced and how effectively they are allocated for the aim of increasing human well-being (Roberts et al., 2020; Rao and Wilson, 2021).

An essential aspect of human well-being is that it depends on multiple human needs, all of which must be met to enable a high quality of life (Jackson et al., 2004; Costanza et al., 2007; Gough, 2017). Strong increases in well-being can be achieved through the satisfaction of needs that are deprived, while little can be gained from needs that are satiated (Sirgy, 2021). A high quality of life can thus be achieved by prioritizing those goods and services that are most crucial. However, while some needs can be satisfied through specific types of consumption, others also require non-market activities.

According to Creutzig et al. (2021), there is significant potential to reduce emissions in a way that is consistent with high levels of well-being. To do so, they suggest that (1) polluting activities of little importance to well-being should be avoided; (2) activities of high importance should, whenever possible, be shifted to low-carbon alternatives; and (3) improvements in carbon efficiency should be focused on activities where such alternatives are missing. An overview of this avoid-shift-improve[1] approach is given in Fig. 1.

How actual mitigation is achieved and ultimately impacts well-being depends on which climate policies are used. While multiple instruments are available for designing climate policy, it is still somewhat contested which of them are most effective to reach the Paris climate goals (Cullenward and Victor, 2020; Penasco et al., 2021; van den Bergh et al., 2021). Many researchers argue that carbon pricing should be the key instrument of climate policy (Newell and

* Corresponding author at: Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Spain.
E-mail address: ivan.savin@uab.cat (I. Savin).

[1] The decomposition of abatement into these three categories is a common idea that can be found under various names such as scale effects, substitution or composition, and efficiency improvements or technique effects (Larch and Wanner, 2017).

https://doi.org/10.1016/j.ecolecon.2023.108070
Received 5 January 2023; Received in revised form 8 September 2023; Accepted 28 November 2023
Available online 8 December 2023

Stavins, 2003; Cramton et al., 2017; Boyce, 2018; Savin and van den Bergh, 2022). In this study we take it as exemplary instrument and consider its interaction with other policy measures. Carbon pricing can be implemented through a carbon tax, where emitters pay a fee per unit of caused emissions; or a permit market, where emitters can trade emission permits (Goulder and Schein, 2013). An alternative approach is to restrict emissions through direct regulation such as an emission quota, which also translates into an implicit carbon price. A key difference between these instruments is that the latter two can cause higher abatement costs due to inefficient selection of abatement options (Foramitti et al., 2021a). Another well-known difference regards windfall profits. This can happen under direct regulation, but also under permit trading if a grandfathering scheme is used to distribute permits for free (Foramitti et al., 2021b). There are further differences between these instruments that are not the focus of this study. For an overview, see Goulder and Schein (2013).

Mitigation can further be aided by improvements of low-carbon infrastructure. The idea of this approach is to provide individuals with additional incentives for the use of low-carbon alternatives apart from carbon pricing. A particular way in which low-carbon alternatives can be made more attractive is by reducing the amount of time they require. The most relevant example for this is the case of mobility, where built infrastructure for walking, cycling, and public transport reduces the amount of time that is required to choose low-carbon modes of mobility. Similar potential for infrastructure improvements has also been found regarding other parts of the economy (Creutzig et al., 2021).

The aim of this study is to examine the performance of a carbon pricing when multiple human needs are taken into account. It uses the method of agent-based models (ABMs), which allows for the representation of economic dynamics based on the interaction of autonomous agents with heterogeneous characteristics (Dawid and Delli Gatti, 2018; D'Orazio and Valente, 2019; Rengs and Scholz-Wäckerle, 2020; Castro et al., 2020; Terranova and Turco, 2022; Savin et al., 2022). ABMs have proven to be flexible enough to integrate elements from different disciplines such as sociology, psychology and economics and therefore are most suitable for this purpose (Savin et al., 2022). The presented model builds upon the Needs & Limits framework introduced by Foramitti (2023), where human individuals try to increase their quality of life and are heterogeneous in regard to both their income and needs. In the present study agents only interact in the labor market and final good markets affecting chances of their peers to find a job or satisfy their needs. Furthermore, as shown in Foramitti (2023), more sophisticated interaction (e.g., imitation or status-comparison) can be implemented in this approach. This demand-side is combined with a supply-side consisting of sectors that produce different types of consumption goods and are able to reduce their emission intensity through the adoption of low-carbon technology. The resulting model makes it possible to analyze how climate policy, through the dynamic behavior of various economic actors, translates into selective growth and decline of different sectors and ultimately into well-being.

Multiple numerical experiments are conducted to compare the performance of different policy approaches. First, we compare the effects of carbon pricing under varying price levels and different schemes for tax revenue recycling. Second, we analyze the impact of two potential side-effects: the presence of windfall profits and the existence of unnecessary abatement costs due to inefficient selection of abatement options. We further consider the impact of low-carbon infrastructure investments in combination with carbon pricing. Finally, the needs-based approach of this model is compared with traditional formulations of social welfare. Reductions in emissions are analyzed based on the relative share of the three strategies: avoid, shift, and improve. The first strategy, avoid – also called reduce – implies that the consumer chooses to use none of or less of a resource. The second strategy, shift – also called maintain – that the consumer switches from a less sustainable method of consumption to a more sustainable one. The last strategy — suggests that the consumer increases the resource efficiency of an existing good or service. Outcomes are evaluated in regard to effectiveness, well-being, and inequality.

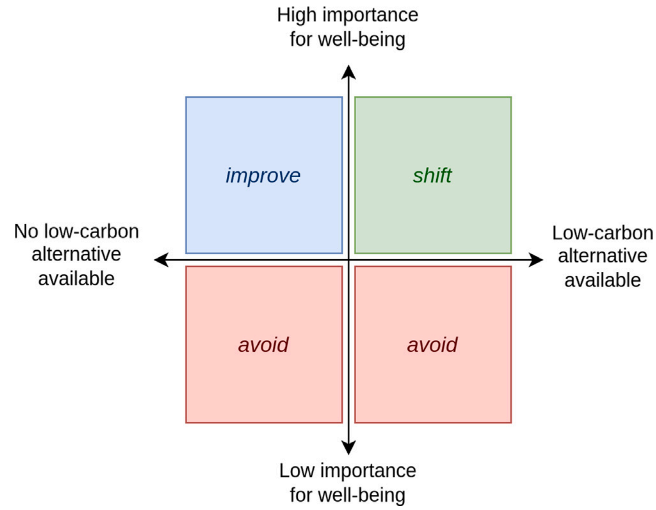


Fig. 1. The avoid-shift-improve framework represent different ways of achieving emission reductions in a way that is consistent with high levels of well-being.

The remainder of this chapter is structured as follows. Section 2 motivates the focus on carbon pricing. Section 3 describes the general model. Section 4 introduces the numerical experiment that is conducted with the model. Section 5 presents the results, while Section 6 concludes.

2. Policy context

Effective emission reduction is likely to require a price on carbon emissions (Baranzini et al., 2017). This approach increases the relative prices of goods and services in proportion to their carbon content, stimulating firms and individuals to take direct and indirect emissions into account in their decisions and switch to low-carbon alternatives. This incentivizes emitters with the lowest marginal abatement costs to act first, which in turn reduces the overall costs of mitigation (Newell and Stavins, 2003).

Within neoclassical economics, carbon pricing is considered the best approach to climate policy as it is able to achieve mitigation at the lowest possible costs to society, which in turn leads to optimal welfare (Pigou, 1920).[2] Even without relying on the notion of optimality, economists have argued that 'carbon pricing is more effective, at a reasonable cost, in reducing emission than other approaches' (Baranzini et al., 2017). Recent models have further shown how revenue recycling can bring additional benefits by reducing inequality and thus increasing well-being of low-income groups (Budolfson et al., 2021).

These advantages of carbon pricing have been criticized from a perspective of human needs, as 'it is only the level of mitigation costs rather than the relevance to human well-being which determines which emissions will cease and which will continue' (Huwe and Frick, 2022). However, carbon pricing will not only affect industry but also individuals — the latter will move away from high-carbon options unless these are essential for their well-being. That is, both individuals and producers will be forced to trade off all costs against all benefits (Baranzini et al., 2017; van den Bergh and Savin, 2021).

Policy conclusions on this matter depend on the objective criteria used for the assessment of social welfare (Botzen and van den Bergh,

[2] While Pigou himself never considered climate policy or the externality of carbon emissions, this result is a special case of his work on environmental externalities and policy.

2014). The conventional economic approach is to look at social welfare in terms of the total utility that can be gained from the consumption of goods. Most models applied to the study of climate policy regard only a single representative good. When multiple types of consumption are taken into account such as in Budolfson et al. (2021), utility is commonly defined through a constant elasticity of substitution (CES) function.

Here, the objective criterion is people's quality of life (QOL), with the aim of policy maker being to reach high average levels with a low disparity. Particular emphasis is put on the fact that multiple human needs must be met to enable a high quality of life (Jackson et al., 2004; Costanza et al., 2007; Gough, 2017). Based on the Needs & Limits framework, this conceptualization of well-being is described through an extended CES function that makes it possible to represent a wide range of psychological characteristics such as the satiability of needs (Foramitti, 2023). QOL is thus representing subjective well-being in the broadest sense. Agents undertake actions in different life domains maximizing their overall satisfaction given their social, economic, and environmental experiences. The present study reports an application of the QOL framework to climate policy contributing to earlier literature that integrates the perspective of needs satisfaction into economic research (Bogdanovych and Trescak, 2016; Jager, 2017; Kangur et al., 2017).

3. Model description

The model consists of n^I human individuals and n^S economic sectors that produce different types of economic goods. Sectors represent different life domains in which agents fulfill their needs. Since agents have limited resources (time, money, etc.), actions of agents face trade-offs in different domains. Individuals are denoted by the index $i \in I = \{1, \dots, n^I\}$. Sectors and their respective goods are denoted by $s \in S = \{1, \dots, n^S\}$. The simulation follows discrete time-steps (or rounds), denoted by $t \in T = \{1, \dots, n^T\}$. The chain of events during each step t is as follows:

1. Sectors decide about their objectives
2. Sectors and individuals interact on the labor market
3. Sectors produce goods and cause emissions
4. Individuals receive income
5. Individuals consume goods and perform activities
6. Sectors adopt technological improvements

The following subsections describe each of these steps in more detail, adhering to the same order.

3.1. Objectives

Each sector sets their desired production level $q^G_{s,t}$ to match their expected demand, which is based on the sector's experienced demand from the previous round $q^D_{s,t-1}$. Following Caiani et al. (2016), this objective is further adjusted by a desired inventory share ν and the existing inventory of unsold goods from the previous round $q^I_{s,t-1}$.

$$q^G_{s,t} = q^D_{s,t-1}(1+\nu) - q^I_{s,t-1} \tag{1}$$

3.2. Labor market

The labor demand of each sector is based on the desired production level $q^G_{s,t}$ and labor intensity μ_s.

$$N^D_{s,t} = q^G_{s,t}\ \mu_s \tag{2}$$

The labor market is represented in a simplified manner, assuming that each sector manages to hire the share of available labor that is proportional to their share of labor demand within the economy:

$$N_{s,t} = \frac{N^D_{s,t}\ n^I}{\sum_{s' \in S} N^D_{s',t}} \tag{3}$$

3.3. Production

Sectors produce goods based on their available workforce $N_{s,t}$ and labor intensity μ_s.

$$q^P_{s,t} = \frac{N_{s,t}}{\mu_s} \tag{4}$$

The emissions of each sector depend on the emission intensity ε_s:

$$e_{s,t} = q^P_{s,t}\ \varepsilon_s \tag{5}$$

The costs per unit of production in each sector depend on the average wage $\overline{w}$, labor intensity μ_s, emission intensity ε_s, and carbon price τ.

$$c_s = \overline{w}\ \mu_s + \tau\ \varepsilon_s \tag{6}$$

The sales price is based on a fixed mark-up rate m on these production costs:

$$p_s = c_s\ (1+m) \tag{7}$$

3.4. Income

Each round, individuals receive the wage w_i as their first source of income. Wages are heterogeneous, and follow an exogenously given income distribution. In addition, individuals receive the recycled revenues from carbon pricing r_t, which depend on each sector's emissions and the part of the carbon price τ that has to be paid as a fee to the regulator. The windfall profit rate[3] χ_1 describes a share of the carbon price that is not paid as a fee to the regulator, which will be explored as a potential side-effect.

$$r_t = \sum_{s \in S} e_{s,t}\ \tau\ (1-\chi_1) \tag{8}$$

The model includes three different ways of recycling the revenue from carbon pricing:

- **Neutral**: Revenues are given out to individuals in proportion to their income — which means that the Gini coefficient of the resulting income distribution remains unchanged.
- **Progressive**: Revenues are split in equal shares between all individuals — which comes down to a scheme of moderately progressive revenue distribution (Konc et al., 2022).
- **Infrastructure improvements**: A share ς of the revenue r_t is used to finance infrastructure improvements from a specific sector s' at a price $p_{s'}$.[4] This reduces the amount of time $\psi_{a,t}$ that is needed to perform an activity a (see Section 3.5). The parameter λ_a describes the effectiveness of these improvements.

$$\psi_{a,t} = \psi^0_a - \varsigma\, r_t\, \frac{\lambda_a}{p_{s'}} \tag{9}$$

As a third and final source of income, remaining profit from both markup m and windfall profits $\tau\ \ \chi_1$ is distributed as dividends to each individual in proportion to their income, assuming in a simplified manner that individuals hold company stocks in relation to their wealth (Caiani et al., 2016).

Note that the carbon tax without any redistribution is neutral with respect to income inequality since we do not assume agents with lower income to have higher consumption of high-carbon good. However, as has been shown in Foramitti (2023), the tax causes an increase in emissions inequality, which reduces emissions more among low-income agents than among high-income agents since the latter are less price-sensitive in their demand. Moreover, without tax revenue redistribution, average QOL is reduced by the tax.

[3] This is a well-known side-effect under permit trading if permits are allocated through grandfathering.

[4] These investments are reminiscent to investments into climate projects (such as investments in public transport), which are considered in many countries as the most supported option to spend carbon tax revenues by the general public (Maestre-Andrés et al., 2021).

3.5. Consumption

The behavior and well-being of individuals is based on the Needs & Limits framework from Foramitti (2023).[5] In each round, individuals choose their behavior from a given set of possible activities $a \in A = \{1, \dots, n^A\}$. The extent to which each activity is undertaken by an individual during each time-step is described by the activity intensity $\alpha_{i,a,t}$. The activity intensity describes the amount of each activity performed by an individual at a time.

These activities lead to the satisfaction of human needs, which in turn leads to fulfillment $q_{i,d,t} \in [0,1]$ within different life domains $d \in D = \{1, \dots, n^D\}$. The impact of each activity on each domain is given by the impact factor $\delta_{a,d}$. Life domains are described as consisting of satiable needs, which means that an activity will add to little additional fulfillment if the needs of that domain are already satiated to a high degree. The strength of this effect is represented by the satiation rate $k_{i,d}$. It is worth noting that unlike (Maslow, 1943), we assume no fixed order between different needs since their relative importance depends on their current level of deprivation (Jackson et al., 2004).

$$q_{i,d,t} = 1 - e^{-k_{i,d} \sum_{a \in A} \alpha_{i,a,t}\, \delta_{a,d}} \tag{10}$$

The quality of life $Q_{i,t} \in [0,1]$ is described as a bounded variable, representing a range from the worst possible life ($Q_{i,t} = 0$) to the best possible life ($Q_{i,t} = 1$). The relationship between the separate life domains and the quality of life is described by a constant elasticity of substitution function, which is able to represent the interaction between different life domains. The parameters ω_d describe the weights of each life domain and σ the substitution factor.

$$Q_{i,t} = \sum_{d \in D} \left(\omega_d\, {q_{i,d,t}}^{\sigma}\right)^{\frac{1}{\sigma}} \tag{11}$$

Some activities regard the consumption of goods from a sector, in which case individuals are restricted by their income budget. Next to budget constraints, consumers have a time constraint which notably affects activities that use infrastructure. As a result, the availability of different types of infrastructure creates more flexibility to meet this second constraint. Similarly, improvements in infrastructure can allow reducing time use of specific activities, such as transport. The impact of each activity on time is given by $\psi_{a,t}$.

During each time-step, individuals try to make the best choice of $\alpha_{i,a,t}$ in order to improve their quality of life. Following Foramitti (2023), this is formalized through a numerical algorithm of constrained optimization, using sequential least square programming. Agents start from their choices of $\alpha_{i,a,t-1}$ from the previous round, and try to adjust the values of $\alpha_{i,a,t}$ in order to reach higher levels of well-being while staying within their given constraints of money and time.

The consumption choices summed over all individuals becomes the experienced demand $q^D_{s,t}$ of each sector. When the total demand for a sector exceeds the available supply for sale, the consumption of each agent is reduced proportionally. If time is freed up in this process, it is used for non-market activities. The resulting consumption becomes a sector's actual sales $q^S_{s,t}$.

3.6. Technological adoption

Sectors are able to adopt new technologies that will reduce their emission intensity. Since labor is the only production input in this model, the cost of this improvement is represented as an increase of labor intensity. This is because low-carbon technologies tend to be more labor-intensive (Fankhauser et al., 2008; Bulavskaya and Reynes, 2018; Fragkos and Paroussos, 2018) and thus can cause additional labor requirements at different points within the supply chain of a sector, including capital production, new material inputs, maintenance, or higher labor requirements in the production of end-use goods.

This cost of technological adoption is represented by the abatement cost factor β_s, which describes the marginal increase in labor intensity $\Delta\mu$ that results from a marginal reduction of the emission intensity $\Delta\epsilon$.[6]

$$\beta_s = \frac{\Delta\mu}{\Delta\epsilon} \tag{12}$$

Sectors choose a level of abatement through technological adoption $\phi_s \in [0,1]$ in order to minimize their production costs. This means that they increase ϕ_s up to the point where the marginal increase in labor intensity would lead to equal costs as the marginal gains from paying less carbon tax. Since production factors are kept constant in this model, this choice does not change over time. This optimal point is derived in Appendix A.

4. Numerical experiments

Multiple numerical experiments are conducted in this study. The computational model is written in Python with the AgentPy package (Foramitti, 2021). The code is available under an open-source license.

The following describes the illustrative setting that is assumed for these experiments. An overview is given in Fig. 2. Parameter values are provided in Appendix B. The model describes two sectors that produce goods for one specific life domain. The first produces a high-carbon good, and the second produces a low-carbon alternative. A third sector represents the rest of the economy, which satisfies an aggregate life domain for all other market-related needs. In addition, the rest of the economy can also produce and sell infrastructure improvements to the policymaker.

Individuals have two resources at hand: money and time. They can use these resources for four activities. The first three represent the consumption of goods from the three sectors, and thus require money. The consumption of the low-carbon good can be further characterized as more time-costly. Without loss of generality we assume henceforth that the high-carbon good does not require consumption time. The amount of time that is required can be reduced through low-carbon infrastructure improvements that are paid for by the policymaker. Finally, individuals can also use their time for non-market activities, which lead to the satisfaction of non-market needs.

A real-world example of this setting would be to think of the specific life domain as the need for mobility. Cars can then be seen as the brown good and public transport or bicycles as the green good. In this example, the three types of abatement would be as follows. Cars could be improved, i.e. made more carbon efficient. Consumption could shift to a different sector like walking, cycling, and public transportation that is able to fulfill the same need for mobility. Improvements of low-carbon infrastructure can represent a wide range of measures in this case, including: vehicle stocks for shared mobility; charging stations for electric vehicles; or built infrastructure such as rails, bike lanes, and pedestrian streets that would make these alternatives more convenient. Finally, the total amount of transportation could be reduced, since not all transportation is essential to well-being. While this example of mobility is suited for illustration, the three strategies of avoid, shift, and improve are also relevant to other parts of the economy (Creutzig et al., 2021).

The described setting consists of 100 individuals, each representing one percentile of a population. Their income rates are calibrated to

[5] Alternative formulations of social welfare for comparison are described in Appendix D. This section provides only a short overview.

[6] In the literature technological change is sometimes modeled in a more sophisticated way (Dawid and Delli Gatti, 2018; Lamperti et al., 2018; Rengs and Scholz-Wäckerle, 2020; Savin, 2021), but since our focus in this study is on the interaction of human needs and climate policy instruments, we leave extensions of this part to further research.

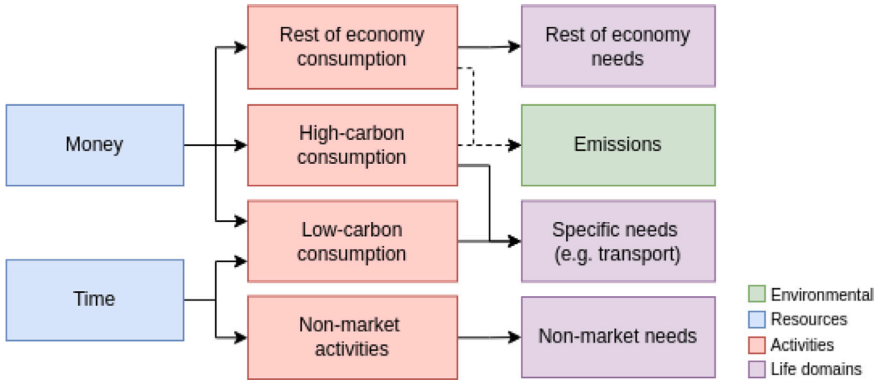


Fig. 2. Overview of agents' resources, activities, and life domains.

follow the global income distribution in 2016, which does not imply that these agents represent the global population but merely display the same degree of inequality as in the real world. The satiation rates of each agent are drawn from a random distribution. The distribution parameters as well as the domain weights are calibrated so that the well-being outcome follows a similar distribution as real-world values of global life-satisfaction. More detail on the parameter choices are given in Appendix B.

The numerical experiments consist of repeated simulations of this setting for different policy parameters. The central parameter of interest is the carbon price τ, with a value $\tau = 0$ representing the no policy or business as usual scenario. The impacts of carbon pricing are analyzed for each of the three revenue recycling methods described in Section 3.4, namely neutral revenue recycling, progressive revenue recycling, and a mix of progressive revenue recycling and expenditure for low-carbon infrastructure improvements (Maestre-Andrés et al., 2021). For the latter, two different cases are considered in which the improvements have either a small or large effect on time-use.

The basic setting of this experiment represents the impacts of a carbon tax. Deviations from this setting are considered to explore the difference in performance if carbon pricing is realized through permit trading or direct regulation. Two effects are identified in Foramitti et al. (2021a,b) as potential side-effects of quantity-based approaches. Instead of reproducing these in the model, we simplify the current setting and reintroduce them exogenously. The two factors are as follows:

1. The windfall profit rate χ_1 describes the case where a part of the resulting carbon price does not become revenue but instead additional profit.
2. The abatement costs error χ_2 (Appendix B) describes increased abatement costs due to inconsistent incentives that lead to an inefficient selection of the cheapest abatement options within each sector. This has been identified as a potential side-effect of both permit trading and direct regulation.[7]

The results of these experiments are analyzed along three different evaluation criteria to study impacts on well-being, effectiveness, and equity:

1. The quality of life that can be achieved at a given level of emission reduction.
2. The amount of mitigation that can be achieved by a given level of carbon price.
3. Distributional impacts on income inequality.

Analysis is further aided by a decomposition of mitigation into the relative contribution of the three categories: avoid, shift, and improve. The derivation of these abatement shares is given in Appendix C.

Finally, the needs-based approach of this study is compared with traditional formulations of social welfare. As shown in Appendix D, social welfare is described in terms of aggregation of individual utilities that are derived from consumption. The following variations are considered. First, the measurement of welfare is based on either prices or on fixed weights. And second, two different ways to aggregate welfare gains from different types of consumption are considered:

1. Linear aggregation of welfare gains over all types of consumption (perfect substitution). This can be seen as the implicit assumption in models that assume only one aggregate consumption good, such as in D'Orazio and Valente (2019).
2. CES aggregation with limited substitution between different types of consumption, such as in Budolfson et al. (2021).

5. Results

5.1. General results

We first look at the impact of carbon pricing for different price levels and recycling schemes. Fig. 3 presents the results. Let us first consider the difference between neutral and progressive recycling. The first plot in Fig. 3 presents the outcome on well-being under different levels of achieved emission reduction. Under a neutral recycling scheme, increased abatement leads to lower levels of well-being. This is because mitigation reduces the availability of high-carbon goods while the low-carbon alternative competes with non-market activities for time. This loss in well-being becomes steeper for higher levels of abatement as the loss of consumption becomes more essential due to the deprivation of needs.

Results show that the decrease of well-being that is caused by mitigation can be counteracted through progressive revenue recycling (note that with progressive revenue recycling QOL rises by about 25%). This recycling increases the purchasing power of low-income individuals who are able to substantially improve their quality of life with small amounts of additional income. The negative effect of this change on high-income individuals is small in comparison as their needs are already satiated to a high degree. Average well-being is thus higher under progressive than under neutral recycling.

The second plot in Fig. 3 demonstrates the effectiveness of carbon pricing: it shows that amount of emission reduction that can be achieved (and thus damage to the environment that can be avoided) under a given carbon price level. The lower this curve, the lower the

[7] This is because the prior literature has shown that when firms abate emissions through innovation, permit trading can lead to a fall in prices that can drive green firms out of the market and make their low-emission technology into stranded assets (Foramitti et al., 2021a). Therefore, some firms may abate too much and then go bankrupt while other firms abate too little because of this uncertainty.

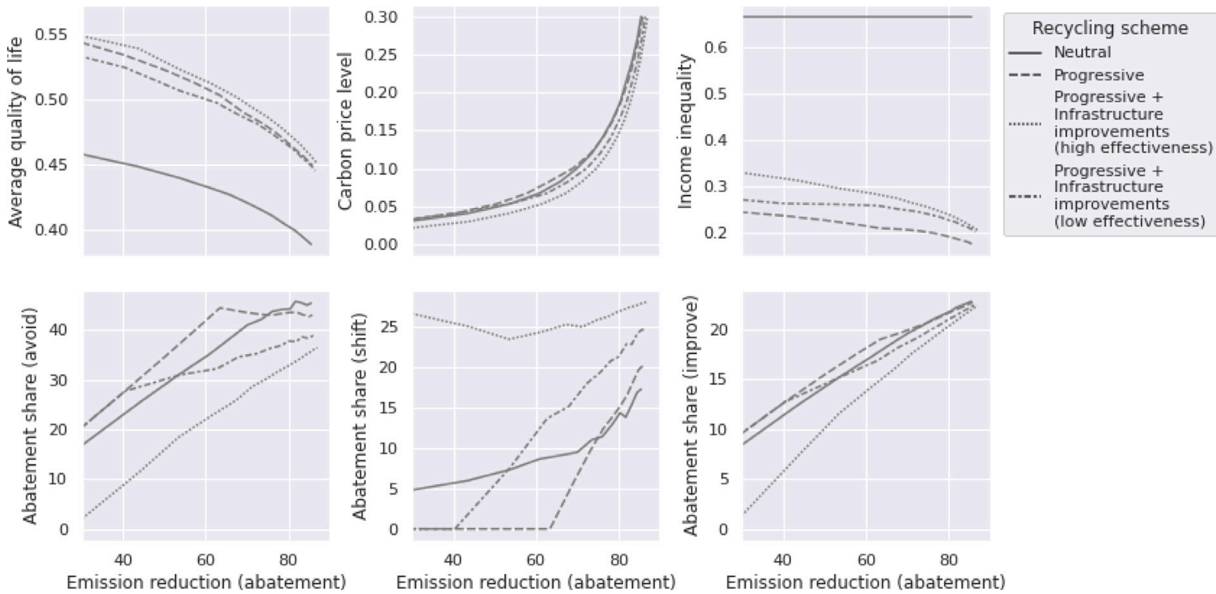


Fig. 3. Comparison of different carbon tax levels and recycling schemes. The first row shows well-being outcomes, effectiveness, and distributional impacts. The second row shows the shares of abatement through the factors avoid, shift, and improve.

carbon price that is required to achieve a same amount of abatement. In other words, carbon pricing is seen as more effective if it can achieve the same level of abatement with a lower carbon price level. Results show that the marginal effect of carbon pricing is reduced for higher price levels, as cheaper opportunities for abatement become exhausted. The recycling scheme is shown to have almost no impact with respect to this measure of effectiveness.

The third plot in Fig. 3 presents the Gini coefficient of the income distribution. The higher this coefficient, the higher income inequality. By design, the neutral recycling scheme does not affect this measure. The progressive recycling scheme, in contrast, leads to a reduction in income inequality. This is counteracted by the fact that the revenue from carbon pricing is based on the amount of emissions and thus declines when emissions are reduced. The reduction of inequality is thus slower than the increase in carbon price that can be seen in the second plot.

The second row of Fig. 3 regards how emission reduction is achieved, decomposed into the three categories of avoid, shift, and improve. Shift is shown to happen earlier under neutral recycling. This is because there are more individuals with a low income in this case, who are more willing to use their time for the low-carbon alternative since they benefit more from saving money than from saving time. A higher share of shift leads to lower shares of avoid and improve since the three shares of abatement have to sum up to the total amount of abatement (Appendix C).

Next, we look at the effect of using part of the revenue from carbon pricing for low-carbon infrastructure improvements while the rest is still distributed through progressive recycling. Fig. 3 shows that such improvements increase the shift to low-carbon alternatives, which in turn increases the effectiveness of a carbon price in reducing emissions.[8] Inequality is higher in this case as less revenue is available for progressive recycling. The impact of infrastructure improvements on well-being depends on the ratio between their effectiveness and their costs. If the reduction of time-use per unit of revenue used is low, they lead to lower well-being, since labor is taken away from forms of production that serve human needs. In the opposite case, well-being can be increased as there is more time available for non-market activities.

[8] These results are reminiscent of the study by Acemoglu et al. (2016).

Finally, we examine how these results change under the side-effects outlined in Section 4 that are meant to represent potential side-effects of realizing a carbon price, at least partly, through quantity-based approaches like a permit market or direct regulation. The progressive recycling scheme applies to all of the following results.

The first side-effect regards the case of windfall profits. Results are presented in Fig. 4. The main effect of windfall profits is that they increase income inequality, and thus reduce well-being. As already discussed, higher inequality causes a shift towards low-carbon alternatives to already happen under lower levels of abatement. Notably, this change in income distribution has almost no impact on the carbon price that is needed to achieve a given level of abatement. Outcomes under windfall profits are thus similar to outcomes under a less progressive recycling scheme.

The second side-effect regards increased abatement costs. Results are presented in Fig. 5. Higher abatement costs reduce the effectiveness of carbon pricing, which means that a higher carbon price is necessary to reach a given level of abatement. The increased carbon price means that there is also more revenue from carbon pricing, which reduces income inequality. However, this does not result in higher levels of well-being as the quality of life is at the same time negatively affected by the requirement of achieving emission reductions through a higher share of 'shift' and 'avoid'.

The sensitivity of the presented results towards changes in parameter values for sectors' labor intensity and emission intensity is presented in Appendix E. The sensitivity analysis shows that the relative importance of the three factors (avoid, shift, and improve) can change under different parameter values. This means that – in addition to the mechanisms described above – the impact of carbon pricing strongly depends on the applied setting and particular industrial characteristics.

5.2. Comparison of social welfare functions

Finally, we compare the well-being outcomes under progressive recycling (Fig. 6a) with traditional formulations of social welfare (Fig. 6b). The top row of Fig. 6b shows the case of perfect substitution, calculated as the sum of welfare gains over all types of consumption. The bottom row shows social welfare that is based on a CES function, where there is limited substitution between different types of consumption (Appendix D).

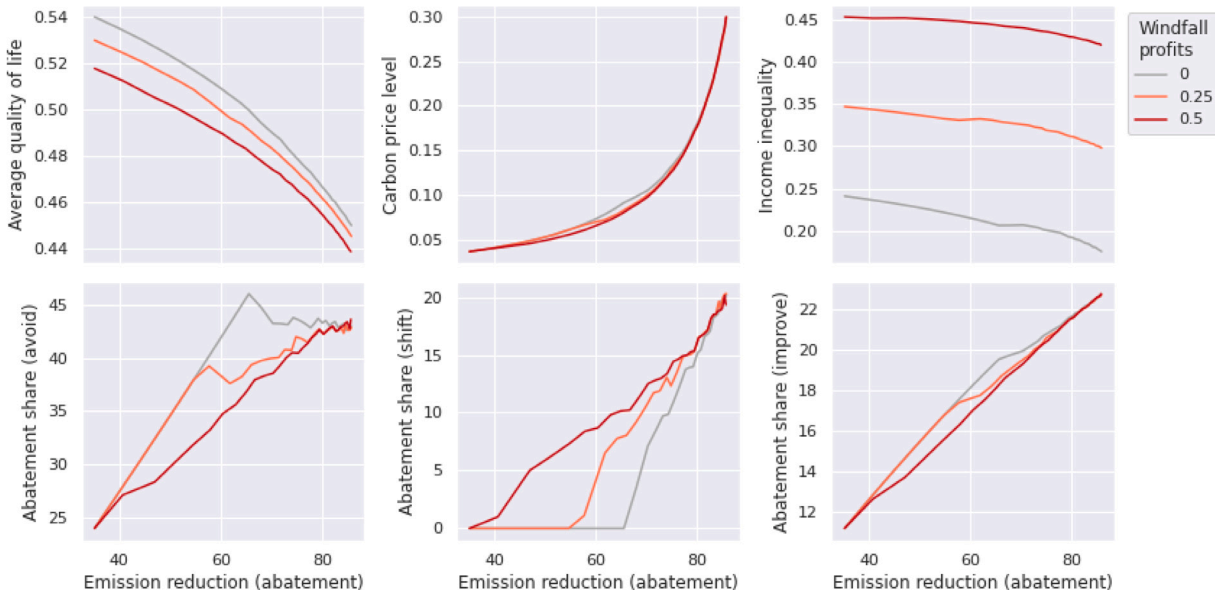


Fig. 4. Policy performance under different levels of windfall profits.

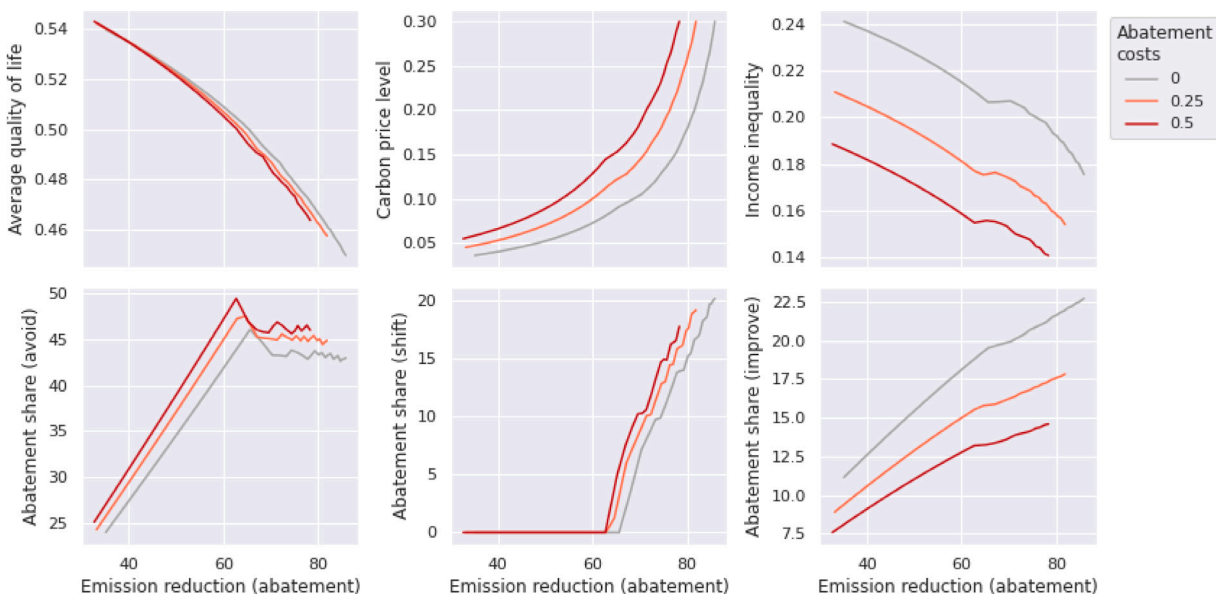


Fig. 5. Policy performance under different levels of abatement costs.

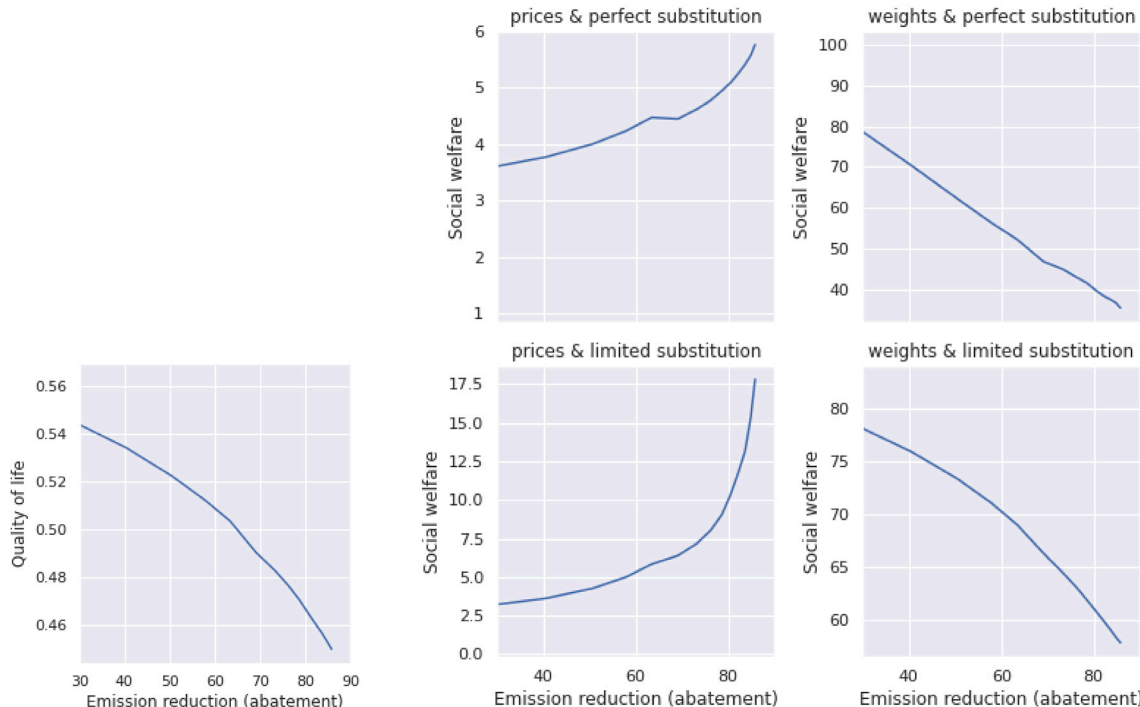
The left column of Fig. 6b presents results when welfare is measured based on current prices. In this case, abatement leads to higher welfare under both perfect and limited substitution. This is because the price of polluting goods is increased through carbon pricing in two ways. First, because the carbon price is added to the price of goods. And second, because the adoption of low-carbon technology can increase production costs.

In the right column of Fig. 6b, the welfare gains from different types of consumption are calculated based on fixed weights. Under perfect substitution, abatement leads to a mostly linear decrease of social welfare. This is because all types of consumption matter equally. Under limited substitution, the results appear similar to the needs-based description of quality of life shown in Fig. 3. Amongst the tested social welfare functions, the CES aggregation with fixed weights can thus be seen as the best proxy for the needs-based approach presented in this study.

6. Conclusions

This paper has presented an agent-based model to explore the demand-side performance of different climate policies, taking into account that there are multiple dimensions to human well-being. The model describes the interaction between various economic sectors and heterogeneous individuals who are trying to increase their quality of life. Policy performance is measured through the criteria of well-being impacts, effectiveness, and inequality — as well as the way in which abatement is achieved.

Our results show that the welfare impact of carbon pricing strongly depends on the way in which revenues are recycled. This is in line with recent literature, which argues that progressive recycling can benefit well-being (Klenert and Mattauch, 2016; Budolfson et al., 2021; Zhao et al., 2022). Here, we add to the literature by demonstrating how progressive recycling can avoid negative impacts on well-being by



(a) (b)

Fig. 6. Policy performance under different formulations of social welfare. Left panel (a) shows the needs-based approach of this study (see Section 3.5). Right panel (b) shows traditional social welfare functions (see Appendix D).

preventing the deprivation of needs. Another contribution of this paper is assessing the role of carbon pricing not only for needs fulfilled by market goods and services but also other needs (fulfilled by informal activities). No mechanism is found to support the argument of Huwe and Frick (2022) that carbon pricing's focus on abatement costs leads to adverse effects in relation to human needs.

The impact of two potential factors has been tested to represent potential side-effects of establishing a carbon price through permit trading or direct regulation instead of a carbon tax. The first regards windfall profits. They are shown to increase inequality as they reduce the amount of revenue that can be recycled — in turn leading to lower levels of well-being. The second regards increased abatement costs. This negatively impacts effectiveness, as it reduces the share of emission reduction that can be achieved through technological adoption.

These results suggest that the best way to achieve emission reduction as well as a higher level of well-being is through either a carbon tax or a well-designed form of permit trading that is able to avoid windfall profits and provides clear incentives for abatement to prevent unnecessary abatement costs. Finally, we find that the performance of carbon pricing can be enhanced through improvements of low-carbon infrastructure. Moreover, we demonstrate that spending carbon tax revenues on infrastructure improvements can create valuable synergy effects to reach a higher QOL, something that has been only argued earlier (Creutzig et al., 2021) without providing a formal proof. The infrastructure investments accelerate the shift towards low-carbon alternatives by enhancing policy effectiveness as well as generating higher levels of well-being, provided the time-saving effect of these improvements is sufficiently high.

Finally, results are compared with traditional formulations of social welfare. We find that the needs-based approach presented in this study resembles the traditional description of social welfare with a CES aggregation and fixed weights since both demonstrate that abatement leads to lower welfare. However, there are three key differences. First, the welfare function has no upper bound, which makes it difficult to allow for a qualitative interpretation of the numerical values. Second, social welfare is aggregated over all individuals, which makes it difficult to represent the deprivation of needs of single individuals. And third, non-market factors of welfare like time-use are not taken into account.

The presented research has a number of limitations. First of all, model complexity results in long computation times and difficulty to calibrate and validate its results. The latter can be mitigated through the use of detailed empirical data sets like in Kangur et al. (2017) and van Praag and Ferrer-i-Carbonell (2004). It should be noted that our aim in this study was not to reproduce exactly any particular country, industry or society. Instead, we focus on a stylized model with a small number of agents for illustrative purposes. Further research is needed to test whether these results will hold in various real-world settings. Extensions of the model could test how impacts vary for diverse parts of the economy that have different possibilities to avoid, shift, and improve. Realism can further be increased through calibration of production factors and elasticity of substitution between level of infrastructure and time to empirical data. Finally, a comparison with other welfare approaches can help to understand how different conceptual approaches to well-being can affect policy conclusions.

Another limitation of the present model is that any quantitative approach to human well-being is a simplification of the human experience. As Joshanloo et al. (2019) noted earlier, every existing measure of well-being provides an incomplete picture. Moreover, since there are multiple philosophical perspectives on well-being, these views might sometimes contradict each other. While we tried to be as careful as possible in this regard, these problems cannot be dismissed completely.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgment

This study has received funding through an ERC Advanced Grant from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement N°741087).

Appendix A. Technological adoption choice

A sector's emission intensity ε_s can be decomposed into a default value ε_s^0 and a difference $\Delta\varepsilon_s$ that is achieved through the adoption of low-carbon technology.

$$\varepsilon_s = \varepsilon_s^0 + \Delta\varepsilon_s \tag{13}$$

As explained in Section 3.6, improvements of emission intensity come at the cost of labor intensity. Applying the abatement cost factor β_s from Eq. (12), a sector's labor intensity can be defined as follows:

$$\mu_s = \mu_s^0 + \Delta\mu = \mu_s^0 + \Delta\varepsilon_s\,\beta_s \tag{14}$$

The definition of a sector's production costs c_s from Eq. (6) can then be rewritten as follows:

$$c_s(\Delta\varepsilon_s) = \overline{w}\,(\mu_s^0 + \beta_s\Delta\varepsilon_s) + \tau\,(\varepsilon_s^0 + \Delta\varepsilon_s) \tag{15}$$

Each sector wants to choose a level of technological adoption so that this cost is minimized, which is described by the following condition.

$$\frac{d}{d\Delta\varepsilon_s}\,c_s(\Delta\varepsilon) = \tau - (\beta_s\,\overline{w})((\mu_s^0 + \Delta\varepsilon_s\,\beta_s)^2) = 0 \tag{16}$$

This describes the point where the marginal benefit from a reduction of emission intensity equals the marginal costs from an increase in labor intensity. The condition can be rewritten to find the optimal abatement level ϕ_s, which is defined as the relative reduction of the default emission intensity:

$$\phi_s = -\frac{\Delta\varepsilon_s}{\varepsilon_s^0} \tag{17}$$

The optimal abatement level then becomes:

$$\phi_s = \frac{1}{\varepsilon_s^0}\left(\frac{\mu_s^0}{\beta_s} - \sqrt{\frac{\overline{w}}{\beta_s\,\tau}}\right) \tag{18}$$

Appendix B. Parameter values

Table 1 presents the parameter values of the model. Values are chosen in order for the illustrative setting to display visible effects in regard to all three types of mitigation (shift, avoid, and improve). The wages w_i follow the world's income distribution in the year 2016, as reported in World Inequality Lab (2021). These wages are normalized so that the total income of all agents sums up to one. At the beginning of a simulation, sectors start with no inventory $q_{s,0}^I = 0$ and expect equal shares in demand $q_{s,0}^D = 1/n^S$.

The satiation rates $k_{i,d}$ for each of the three life domains are heterogeneous amongst agents, and drawn randomly from a normal distribution that is truncated to include only positive values. The mean and standard deviation of these distributions, as well as the domain weights ω_d, are calibrated to be in a similar range as global self-reported life-satisfaction between 2014–2016, as reported in Helliwell et al. (2017). The calibration procedure is the same as in Foramitti (2023).

Within the numerical experiments, several parameters are varied. Values are chosen in order to contribute to the visibility of the discussed mechanisms. The tax rate τ is varied between 0 and 0.3. The recycling scheme is varied between 'neutral' and 'progressive' – as described in Section 3.4. The infrastructure parameters ς and λ_a are generally set to zero, except for two scenarios where a share $\varsigma = 0.15$ is used for low-carbon infrastructure improvements while the rest is still used for progressive recycling. Two cases are considered where the effectiveness of these improvements on low-carbon consumption (λ_a) is set to either 0.005 or 0.01. The parameters χ_1 and χ_2 are further varied from 0 to 0.6. The latter changes the parameters β_s so that a value of e.g. $\chi_2 = 0.1$ increases the value of β_s by 10 %. Finally, the parameters μ_s and ε_s are varied by ±30 % within the sensitivity analysis in Appendix E.

Table 1
Parameter values.

Parameter	Symbol	Values
Number of individuals	n^I	100
Number of sectors	n^S	3
Number of rounds	n^T	10
Number of activities	n^A	4
Number of life domains	n^D	3
Initial labor intensity	μ_s^0	1, 1, 1
Initial emission intensity	ε_s^0	1, 0, 1
Abatement costs	β_s	2, 0, 2
Utility weights	η_s	1, 1, 1
Domain weights[a]	ω_d	0.12, 0.16, 0.73
Satiation rates (mean)[a]	k_d	1.13, 1.30, 1.04
Satiation rates (std)[a]		1.96, 1.84, 0.57
Activity impacts on CoA needs	$\delta_{a,1}$	1, 1, 0, 0
Activity impacts on RoE needs	$\delta_{a,2}$	0, 0, 1, 0
Activity impacts on non-market needs	$\delta_{a,3}$	0, 0, 0, 1
Activity impacts on time	ψ_a^0	0, −1, 0, −1
Substitution rate	σ	0.1
Desired inventory share	ν	0.1
Markup rate	m	0.1

Note: Multiple values are given for parameters with indices, indicating that this parameter has different values for each sector (s), life domain (d), or activity (a).
[a] Calibrated parameters.

Appendix C. Decomposition of abatement

The economy's total abatement A is defined as the amount of saved emissions in comparison to the setting where $\tau = 0$, which is indicated as BAU (business as usual). The values of each variable represent the state of that variable in the last time-step of the simulation.

$$A = -\sum_{s=1}^{N}\Delta e_s = \sum_{s=1}^{N}\left(e_s^{BAU} - e_s\right) \tag{19}$$

The achieved amount of emission reduction are decomposed into three different abatement shares, which can be related to the avoid-shift-improve framework as follows:

1. **Avoid**: A change in overall production of the sector due to a reduction of output.
2. **Shift**: A compositional change within the sector due to a shift from high- to low-carbon firms.
3. **Improve**: A change in emission intensity due to adoption of low-carbon technology.

The decomposition is given by the following equation, as derived in Foramitti (2023):

$$A = -\overline{G}\sum_{s=1}^{N}\left(\Delta\rho_s\,\overline{\xi}_s\right) - \Delta G\sum_{s=1}^{N}\left(\overline{\rho}_s\,\overline{\xi}_s\right) - \sum_{s=1}^{N}\left(\Delta\xi_s\,\overline{g}_s\right) \tag{20}$$

The factor g_s describes the amount of production in each sector. To make the goods of different sectors comparable, their amount is measured in relation to their prices in the BAU scenario.

$$g_s = q_s^P * p_s^{BAU} \tag{21}$$

Similarly, an adjusted emission intensity has to be used:

$$\xi_s = \frac{e_s}{g_s} \tag{22}$$

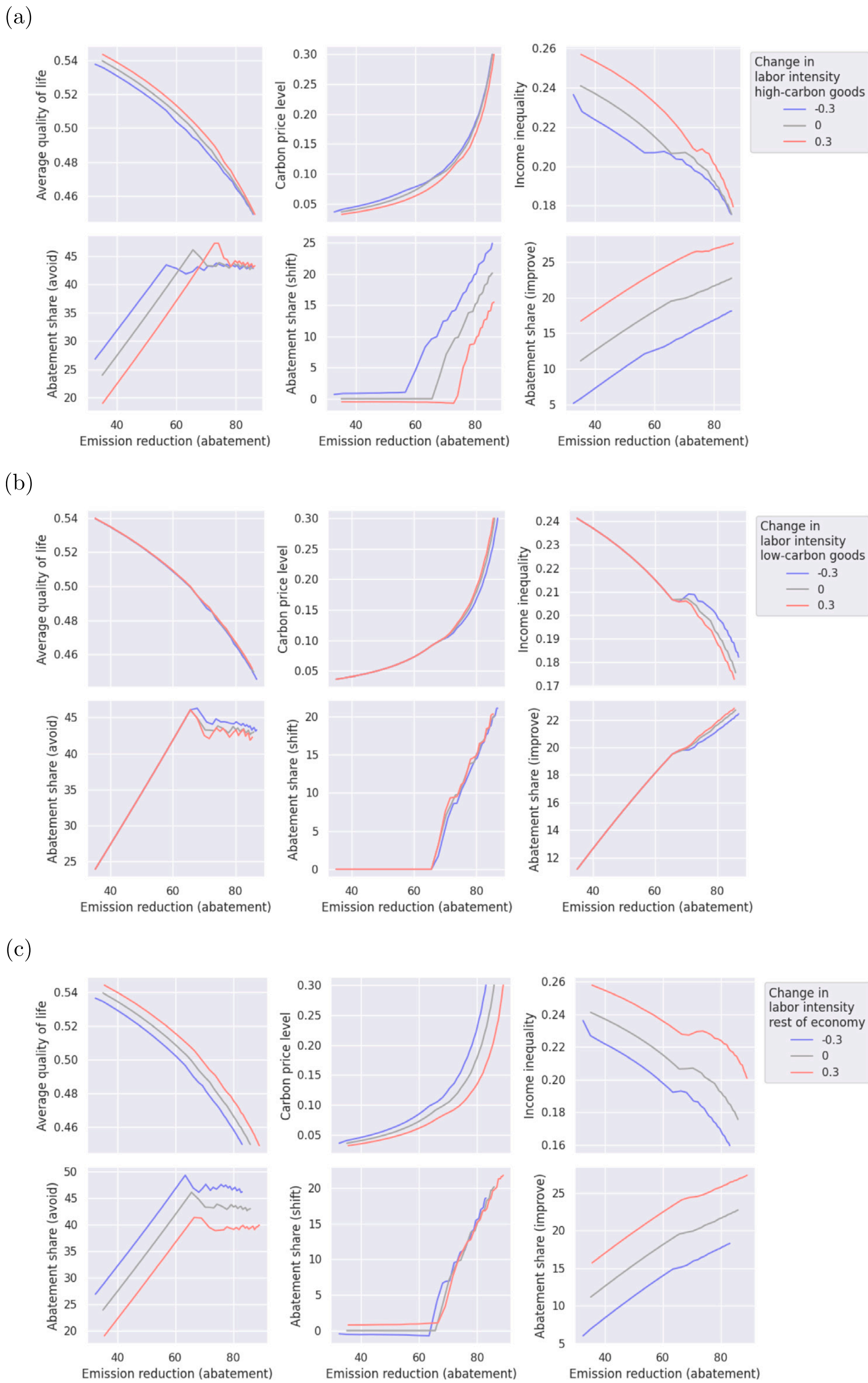


Fig. 7. Policy performance under different values of labor intensity.

The factor G describes the total amount of production.

$$G = \sum_{s=1}^{N} g_s \tag{23}$$

The factor ρ describes each sector's relative share of production:

$$\rho_s = \frac{g_s}{G} \tag{24}$$

The factor Δ refers to the difference of a variable in comparison to the BAU scenario:

$$\Delta x = x - x^{BAU} \tag{25}$$

And a bar refers to the average between these two values:

$$\overline{x} = \frac{x + x^{BAU}}{2} \tag{26}$$

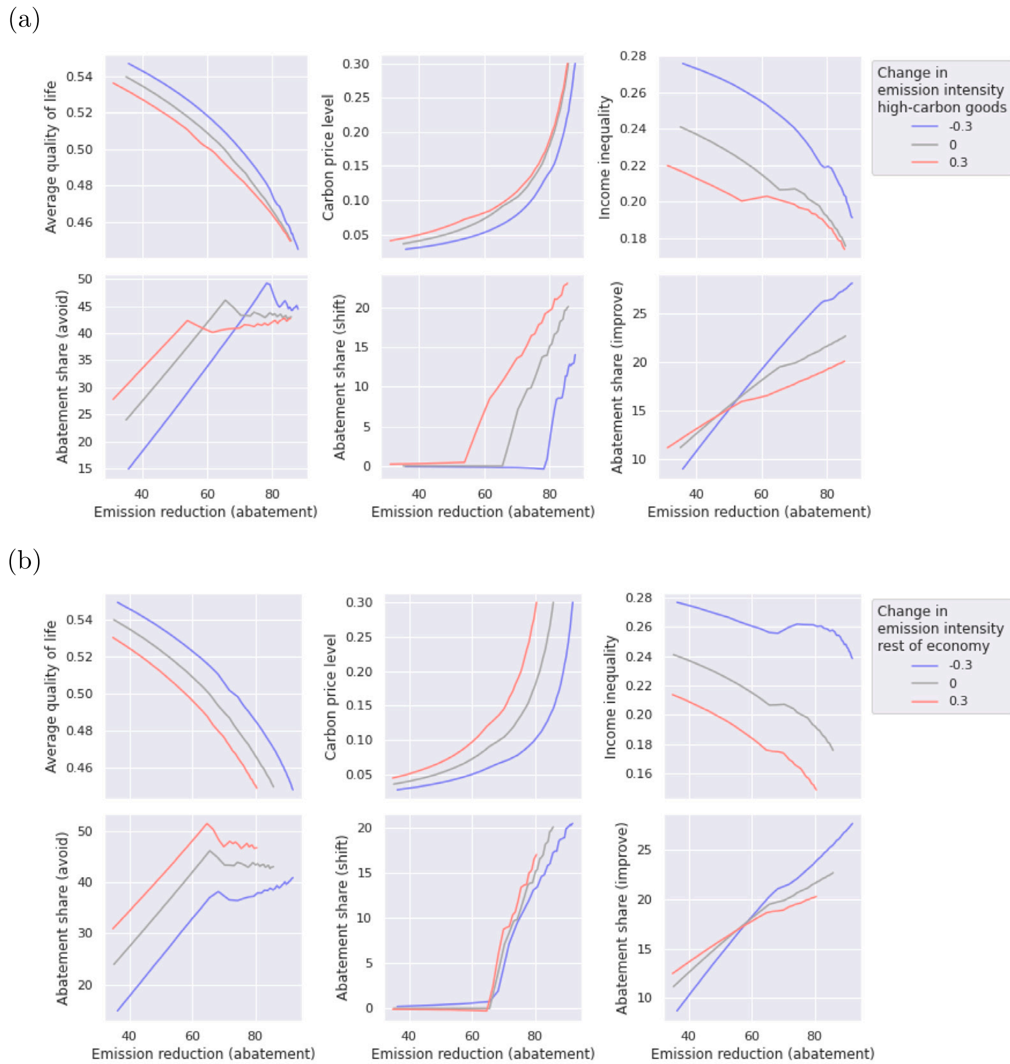


Fig. 8. Policy performance under different values of emission intensity.

Appendix D. Social welfare functions

The following social welfare formulations are considered for comparison with the needs-based approach described in Section 3.5. In line with traditional economic literature, welfare is described in terms of utility that is derived from consumption. A common way of measuring the welfare gains from each type of consumption is in terms of its current price:

$$u^1_{s,t} = q^S_{s,t}\, p_s \tag{27}$$

Alternatively, the welfare gains from each type of consumption can be described based on fixed weights η_s:

$$u^2_{s,t} = q^S_{s,t}\, \eta_s \tag{28}$$

We consider two ways in which the welfare gains from different types of consumption are aggregated. The first is a simple sum of all utilities, which implies perfect substitution between all types of consumption.

$$U^1_t(u_{s,t}) = \sum_{s \in S} u_{s,t} = u_{1,t} + u_{2,t} + u_{3,t} \tag{29}$$

The second way is to use a constant elasticity of substitution (CES) function. In line with the presented setting (see Fig. 2), we assume that the high-carbon and low-carbon sectors ($s \in \{1,2\}$) can substitute each other, while there is limited substitution between these two sectors and the rest of the economy ($s = 3$).

$$U^2_t(u_{s,t}) = \left((u_{1,t} + u_{2,t})^\sigma + (u_{3,t})^\sigma\right)^{\frac{1}{\sigma}} \tag{30}$$

Based on these definitions, four different formulations of social welfare can be described:

1. $U^1_t(u^1_{s,t})$: Based on prices, with perfect substitution
2. $U^1_t(u^2_{s,t})$: Based on weights, with perfect substitution
3. $U^2_t(u^1_{s,t})$: Based on prices, with limited substitution
4. $U^2_t(u^2_{s,t})$: Based on weights, with limited substitution

Appendix E. Sensitivity analysis

This appendix examines the sensitivity of the model towards different parameter values of labor intensity μ_s and emission intensity ε_s. Note that these parameters are different for each sector, with the three sectors of the model being a high-carbon sector, a low-carbon alternative to the high-carbon sector, and the rest of the economy (Section 4). The progressive recycling scheme applies to all of the following results.

Fig. 7 presents the impact of variations in labor intensity. For the high carbon sector (Fig. 7a), a reduction in labor intensity results in higher levels of technological adoption. This reduces the overall emission intensity and thus also the need for 'shift' and 'avoid', increasing both well-being and effectiveness. However, it also leads to higher inequality as there is less revenue from carbon pricing.

A lower labor intensity in the low-carbon sector (Fig. 7b) has a smaller effect, since the choice to consume this good does not just depend on prices but also on time use. A lower labor intensity is shown to increase the share of 'shift' and 'improve', while there is less need for 'avoid'. Once there has been a shift towards this sector, a higher carbon price is needed to reach the same level of abatement. There is thus more revenue from carbon pricing and less inequality.

Changes in labor intensity within the rest of the economy (Fig. 7c) have similar effect as for the high-carbon sector. Again, a lower level of labor intensity leads to increases in effectiveness, well-being, and inequality. A key difference between the two cases can be found in the abatement shares, where changes of labor intensity in the rest of the economy do not affect the share of 'shift'. Improvements from technological adoption instead lead to a larger reduction in the share of 'avoid'.

Fig. 8 presents results regarding variations of emission intensity. The low-carbon sector is excluded here as it causes no emissions. In both of the other sectors, a higher emission intensity results in lower effectiveness as well as a lower quality of life. While technological adoption is initially higher in this case, this is reversed for higher levels of abatement. Again, the main difference between the high-carbon sector (Fig. 8a) and the rest of the economy (Fig. 8b) is that the latter does not affect the share of 'shift' and thus has a bigger impact on the share of 'avoid'.

References

Acemoglu, D., Akcigit, U., Hanley, D., Kerr, W., 2016. Transition to clean technology. J. Political Econ. 124 (1), 52–104.
Baranzini, A., van den Bergh, J.C.J.M., Carattini, S., Howarth, R.B., Padilla, E., Roca, J., 2017. Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. Wiley Interdiscip. Rev. Clim. Change 8 (4).
Bogdanovych, A., Trescak, T., 2016. Generating needs, goals and plans for virtual agents in social simulations. In: Traum, D., Swartout, W., Khooshabeh, P., Kopp, S., Scherer, S., Leuski, A. (Eds.), Intelligent Virtual Agents. In: Lecture Notes in Computer Science, Springer, Cham.
Botzen, W., van den Bergh, J.C., 2014. Specifications of social welfare in economic studies of climate policy: overview of criteria and related policy insights. Environ. Resour. Econ. 58 (1), 1–33.
Boyce, J.K., 2018. Carbon pricing: Effectiveness and equity. Ecol. Econom. 150, 52–61.
Budolfson, M., Dennig, F., Errickson, F., Feindt, S., Ferranna, M., Fleurbaey, M., Klenert, D., Kornek, U., Kuruc, K., Méjean, A., et al., 2021. Climate action with revenue recycling has benefits for poverty, inequality and well-being. Nature Clim. Change 11, 1111–1116.
Bulavskaya, T., Reynes, F., 2018. Job creation and economic impact of renewable energy in the netherlands. Renew. Energy 119, 528–538.
Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., Stiglitz, J.E., 2016. Agent based-stock flow consistent macroeconomics: Towards a benchmark model. J. Econom. Dynam. Control 69, 375–408.
Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., van den Bergh, J., 2020. A review of agent-based modeling of climate-energy policy. Wiley Interdiscip. Rev. Clim. Change e647 (May 2019), 1–26.
Costanza, R., Fisher, B., Ali, S., Beer, C., Bond, L., Boumans, R., Danigelis, N.L., Dickinson, J., Elliott, C., Farley, J., Gayer, D.E., Glenn, L.M.D., Hudspeth, T., Mahoney, D., McCahill, L., McIntosh, B., Reed, B., Rizvi, S.A.T., Rizzo, D.M., Simpatico, T., Snapp, R., 2007. Quality of life: An approach integrating opportunities, human needs, and subjective well-being. Ecol. Econom. 61 (2–3), 267–276.
Cramton, P., MacKay, D., Ockenfels, A., Stoft, S., 2017. Global Carbon Pricing: The Path To Climate Cooperation. The MIT Press.
Creutzig, F., Niamir, L., Bai, X., Cullen, J., Díaz-José, J., Figueroa, M., Grübler, A., Lamb, W., Leip, A., Masanet, E., et al., 2021. Demand-side solutions to climate change mitigation consistent with high levels of wellbeing. Nature Clim. Change.
Cullenward, D., Victor, D., 2020. Making Climate Policy Work. Polity Press, Cambridge.
Dawid, H., Delli Gatti, D., 2018. Agent-based macroeconomics. In: Hommes, C., LeBaron, B. (Eds.), Handbook of Computational Economics, Vol. 4. Elsevier, pp. 63–156.
D'Orazio, P., Valente, M., 2019. The role of finance in environmental innovation diffusion: An evolutionary modeling approach. J. Econ. Behav. Organ. 162, 417–439.
Fankhauser, S., Sehlleier, F., Stern, N., 2008. Climate change, innovation and jobs. Climate Policy 8 (4), 421–429.
Foramitti, J., 2021. Agentpy: A package for agent-based modeling in python. J. Open Source Softw..
Foramitti, J., 2023. A framework for agent-based models of human needs and ecological limits. Ecol. Econom. 204 (Part A), 107651.
Foramitti, J., Savin, I., van den Bergh, J.C., 2021a. Emission tax vs. permit trading under bounded rationality and dynamic markets. Energy Policy 148, 112009.
Foramitti, J., Savin, I., van den Bergh, J.C., 2021b. Regulation at the source? Comparing upstream and downstream climate policies. Technol. Forecast. Soc. Change 172, 121060.
Fragkos, P., Paroussos, L., 2018. Employment creation in EU related to renewables expansion. Appl. Energy 230, 935–945.
Gough, I., 2017. Recomposing consumption: defining necessities for sustainable and equitable well-being. Phil. Trans. R. Soc. A 375 (20160379).
Goulder, L.H., Schein, A.R., 2013. Carbon Taxes Versus Cap and Trade: A Critical Review. Climate Change Econ. 04 (03), 1350010.
Helliwell, J., Layard, R., Sachs, J., 2017. World Happiness Report 2017. Sustainable Development Solutions Network, New York.
Huwe, V., Frick, M., 2022. Far from optimal? Exploring the normative premises and politics of carbon pricing. Energy Res. Soc. Sci. 86, 102458.
Jackson, T., Jager, W., Stagl, S., 2004. Beyond insatiability – needs theory, consumption and sustainability. In: The Ecological Economics of Consumption. Edward Elgar Publishing, Cheltenham, UK.
Jager, W., 2017. Enhancing the realism of simulation (EROS): On implementing and developing psychological theory in social simulation. J. Artif. Soc. Soc. Simul. 20 (3).
Joshanloo, M., Jovanović, V., Taylor, T., 2019. A multidimensional understanding of prosperity and well-being at country level: Data-driven explorations. PLoS One 14 (10), e0223221.
Kangur, A., Jager, W., Verbrugge, R., Bockarjova, M., 2017. An agent-based model for diffusion of electric vehicles. J. Environ. Psychol. 52, 166–182.
Klenert, D., Mattauch, L., 2016. How to make a carbon tax reform progressive: The role of subsistence consumption. Econom. Lett. 138, 100–103.
Konc, T., Drews, S., Savin, I., van den Bergh, J., 2022. Co-dynamics of climate policy stringency and public support. Global Environ. Change 74, 102528.
Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., Sapio, A., 2018. Faraway, so close: coupled climate and economic dynamics in an agent-based integrated assessment model. Ecol. Econom. 150, 315–339.
Larch, M., Wanner, J., 2017. Carbon tariffs: An analysis of the trade, welfare, and emission effects. J. Int. Econ. 109, 195–213.
Maestre-Andrés, S., Drews, S., Savin, I., van den Bergh, J., 2021. Carbon tax acceptability with information provision and mixed revenue uses. Nature Commun. 12 (1), 1–10.
Maslow, A.H., 1943. A theory of human motivation.. Psychol. Rev. 50 (4), 370.
Newell, R.G., Stavins, R.N., 2003. Cost heterogeneity and the potential savings from market-based policies. J. Regulat. Econ. 23 (1), 43–59.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1 (2), 88–95.
Penasco, C., Anadon, L.D., Verdolini, E., 2021. Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. Nature Clim. Change 11 (3), 257–265.
Pigou, A.C., 1920. The Economics of Welfare. Macmillan and Co, London.
Rao, N.D., Wilson, C., 2021. Advancing energy and well-being research. Nat. Sustain..
Rengs, B., Scholz-Wäckerle, J., 2020. Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. J. Econ. Behav. Organ. 169, 332–368.
Roberts, J.T., Steinberger, J.K., Dietz, T., Lamb, W.F., York, R., Jorgenson, A.K., Givens, J.E., Baer, P., Schor, J.B., 2020. Four agendas for research and policy on emissions mitigation and well-being. Global Sustain. 3 (e3), 1–7.
Savin, I., 2021. On optimal regimes of knowledge exchange: a model of recombinant growth and firm networks. J. Econ. Interact. Coord. 16, 497–527.
Savin, I., Creutzig, F., Filatova, T., Foramitti, J., Konc, T., Niamir, L., Safarzynska, K., van den Bergh, J., 2022. Agent-based modeling to integrate elements from different disciplines for ambitious climate policy. WIREs Climate Change 14 (2), e811.
Savin, I., van den Bergh, J., 2022. Tired of climate targets: Shift focus of 'IPCC scenarios' from targets to policies. Ann. New York Acad. Sci. 1517 (1), 5–10.
Sirgy, J., 2021. The Psychology of Quality of Life - Wellbeing and Positive Mental Health, third ed. Springer Nature Switzerland.
Terranova, R., Turco, E.M., 2022. Concentration, stagnation and inequality: An agent-based approach. J. Econ. Behav. Organ. 193, 569–595.

van den Bergh, J., Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., 2021. Designing an effective climate-policy mix: Accounting for instrument synergy. Climate Policy 21 (6), 745–764.

van den Bergh, J., Savin, I., 2021. Impact of carbon pricing on low-carbon innovation and deep decarbonisation: controversies and path forward. Environ. Resour. Econ. 80 (4), 705–715.

van Praag, B.M.S., Ferrer-i-Carbonell, A., 2004. Happiness Quantified: A Satisfaction Calculus Approach. Oxford University Press.

World Inequality Lab, 2021. World inequality database. https://wid.world/. (Accessed: 3 June 2021).

Zhao, Y., Wang, C., Cai, W., 2022. Carbon pricing policy, revenue recycling schemes, and income inequality: A multi-regional dynamic CGE assessment for China. Resour. Conserv. Recy. 181, 106246.