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Towards BitCO$_2$, an individual consumption-based carbon emission reduction mechanism

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ABSTRACT

Human activities, such as burning fossil fuels for electricity generation, heating, and transport, are the primary drivers of a large amount of greenhouse gases emission. The individual consumers, able to influence the supply-chains behind the commodities their chose to fulfil their needs is the driver behind production and, consequently, its impacts. Thus, the active and willing participation of citizens in combatting climate change may be pivotal to address this issue. The present work is aimed at presenting and modelling a novel market-based carbon emission reduction mechanism, called BitCO$_2$, designed to incentivize individual consumption choices toward lower carbon footprints. This mechanism is tested for the Italian private transportation sector thanks to an ad hoc developed System Dynamics model. The Battery Electric Vehicle (BEV) adoption, if compared with the Internal Combustion Engine Vehicle (ICEV) one, cause less CO$_2$ emissions per km travelled. After a certain number of travelled km, a BitCO$_2$ token is assigned to BEV owners for each ton of avoided CO$_2$. This token can be exchanged in a dedicated market and used to get a discount on insurance services. Assuming a Social Cost of Carbon of 9.22 [2.13–22.3] €/tonCO$_2$eq, model results show that the BitCO$_2$ mechanism would allow for a cumulated CO$_2$ emission reduction of 973 [68.9–5'230] ktonCO$_2$eq over 20 years of operation with a peak of 39.3 [5.34–189] thousand additional BEV registration per year.

1. Introduction

1.1. Internalizing the social cost of carbon

Human industrial activities have always aimed at satisfying individual needs by producing and consuming goods and services. The sum of the effects of each individual activity results in the social sphere of causation, where human beings interact with each other exchanging value while interacting with the biophysical sphere, thus impacting it to a different degree (Pauliuk and Hertwich, 2015). In this process, humans exploit natural resources and release emissions as side products. The interaction between social and biophysical spheres could trigger feedback loops influencing how stocks and flows of materials, goods, and services are allocated between individuals and environments (Fischer-Kowalski and Weisz, 1999).

In the interaction between human activities and nature, technology has allowed economic development, intended as how the same need can be fulfilled by exploiting fewer resources. The use of resources and the resulting release of emissions as a co-product of society's economic initiatives, has recently led to a high level of pressure on the environment (Steffen et al., 2015; Richardson et al., 2023). Indeed, the release of emissions and overexploitation of resources by economic agents may have an indirect economic impact on a third party, or the society taken as a whole: this economic impact is called externality. If its impact is negative, one way to actively account for it is to endogenize it into the economy by attributing present economic value to potential future damages.

In theory, the environmentally harmful activity should be surcharged by a cost that equals marginal damage with the marginal cost of mitigating that impact (OECD, 2011). However, when it comes to determining marginal external costs (such as climate change-related issues), uncertainties preclude the determination of this value, usually called Social Cost of Carbon (SCC) (Pindyck, 2017). Among various environmental externalities, the ones associated with greenhouse gases (GHG) emissions are currently a focus of policy makers and regulators. Several alternative mechanisms and policies can be adopted to assign an economic cost to GHG-related externalities.

The implementation of theoretically optimal carbon pricing policies,

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such as carbon taxes or emissions trading schemes, may be limited by political economy constraints such as stakeholder interests and low willingness to pay (Jenkins, 2014) (Mildenberger et al., 2021). Some political economists argue that political will is crucial in driving technology development and that policy should encourage system-wide technological progress (Breetz et al., 2018) (Colgan et al., 2021). These may require other policies that do not explicitly price carbon, such as broader industrial policies, which have both advantages and disadvantages. These include the implementation of low-carbon energy subsidies as part of the comprehensive measures outlined in the recent Inflation Reduction Act (White House, 2023). These subsidies aim to promote the adoption of low-carbon technologies in specific sectors and have a direct impact on influencing household consumption preferences. Across the ocean, the European Union recently decided that only zero-emission vehicles will be sold in Europe by 2035 (Mock and Tietge, 2022). To support the automotive industry, a flexible carbon credit market mechanism exists (Mock and Tietge, 2022).

Finally, carbon credits offer a potential alternative to traditional carbon pricing policies, where companies can offset their emissions by purchasing credits from projects that reduce emissions elsewhere. This theoretically creates a market for emissions reductions and incentivizes investment in low-carbon technologies.

All these initiatives can be grouped into the category of Carbon Emission Reduction Mechanisms (CERMs).

1.2. *Objectives of the work*

At present, the world is witnessing the initial stages of a transition in terms of the increased adoption of electric vehicles and the growth in the installation of renewable energy sources (IEA. World, 2022; IRENA, 2022; IEA, 2023). However, despite these positive developments, global emissions levels have yet to decline (Liu et al., 2023). This calls for innovative CERM aimed at reshaping the relationship between consumption and greenhouse gas production.

The individual consumers, able to influence the supply-chains behind the commodities their chose to fulfil their needs is the driver behind production and, consequently, its impacts. To the knowledge of the authors, a market strategy for reducing global GHG emissions which involves individual consumer participation is to date non-existent or under conceptualization and development.

The first purpose of this paper is to propose and explain extensively a novel CERMs that involves both producers and consumers, starting with individual actions. Since a comprehensive evaluation of the mechanism must be conducted to ensure its efficacy, in the absence of empirical testing, a modeling approach can be considered as a minimum requirement. Therefore, the second purpose of this paper is to test the proposed CERM through a modelling approach, simulating its mechanics within a hard to abate sector.

To properly set the stage for a clear introduction of the proposed CERM, a review of current approaches in carbon accounting and footprinting is provided. This completes the current Section 1. Section 2 is addressing the first purpose of the paper, while Section 3 and 4, where the results of the model are analyzed in light of the rules depicted in the formalization of the approach, are fulfilling the second one. Last chapter closes the paper with policy consideration and conclusions (see Fig. 1).

1.3. *Current approaches and limitations*

Carbon emission reduction mechanisms: challenges and alternatives

Joint efforts currently operative at the international level aimed at limiting carbon emissions are grounded on the so-called “territorial” emissions accounting principle. This principle, practically equivalent to Production-Based Approach (PBA), states that each of the nations who took part in international agreements, such as the Paris Agreement (United Nations, 2015), is responsible for the emissions released within its boundaries. Although 23% of global emissions are regulated by carbon pricing initiatives, the need for more comprehensive strategies is underscored by the prospective 2% annual decrease (Green, 2021) (World Bank Group).

It is observed that the price signal of carbon pricing on investors and consumers’ choices, when not hampered by low prices (European Environment Agency, 2016), is often diluted by other taxes and laws, which are usually more impactful on economic agent behavior (Haites, 2018). Although these initiatives have achieved significant local results, the first relevant global outcome has been experienced only in very recent time, when energy-related CO_2 emissions have substantially flattened since 2019 (Liu et al., 2023). However, it should be noted that this results from the sum between a substantial reduction in advanced economies (i.e. EU, USA, and Japan), which have on average a form of carbon limitation policy, and an equal increase in the rest of the world, where carbon emissions are not regulated yet.

In this context, alternative approaches to PBA have emerged in the

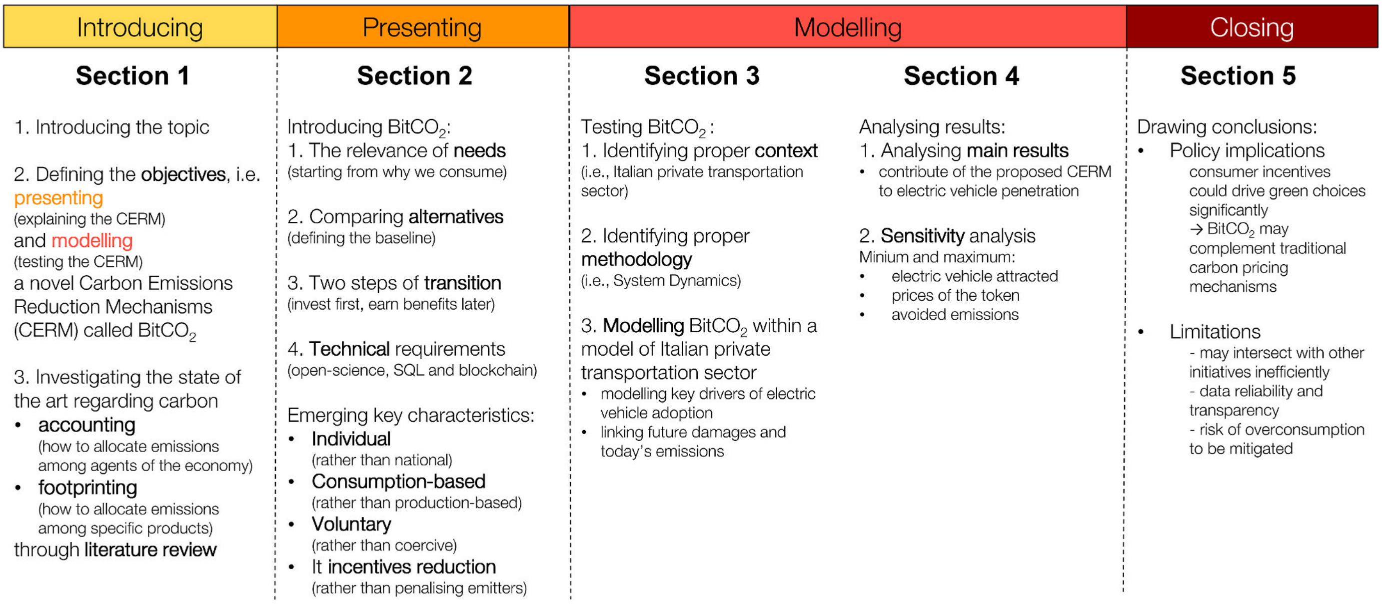

Fig. 1. Graphical representation of the workflow of this research.

scientific (Afionis et al., 2017) and political debate (von der Leyen, 2019) moving toward a Consumption-Based Approach (CBA), which allocates to each country the responsibility for the emission released all over the world to produce what it consumes. In the academic world, several researchers have introduced the possibility of consumption-based schemes, where the consumer – and not the producer – is made responsible for the GHG emissions For further discussion of CBA, the reader is invited to investigate the work of Afionis and colleagues (Afionis et al., 2017). Other authors have proposed third ways to allocate the responsibility of emissions between producers and consumers, suggesting measures for assigning credits and penalties or proportional to economic benefits (Dietzenbacher et al., 2020; Jakob et al., 2021). In practice, a CBA policy may take the form of a border carbon adjustment, assigning a price to emissions embodied in imports (von der Leyen, 2019). CBA effectiveness in unilateral emission reduction policy has been studied (Jakob et al., 2014) and assessed in comparison with PBA, through optimization models (Sommer and Kratena, 2020; Rocco et al., 2020). It emerges that, even if CBA seems to be effective in addressing carbon leakage (i.e. increase in overall CO_2 emission as a consequence of local emission reduction policy), practical regulatory issues, connected to the need for tracking and verifying emission flows, and sub-optimality of the approach hamper the paradigm shift. Furthermore, it is noted that carbon leakage, usually pointed out when unilateral policies are applied in a net carbon importer country, may occur also in the CBA case when applied to a net carbon exporter country, since there would be no incentive for decarbonizing sectors devoted to export (Tukker et al., 2020). Finally, even assuming CBA would perform better than PBA, reforming taxation and international trade agreements (e.g. World Trade Organization) would be needed. Efforts in innovating fiscal policies have recently been explored, describing and evaluating the effects of a destination-based cash flow taxation (Auerbach et al., 2017).

Carbon pricing initiatives have been advocated as the first-best policy able to optimally fix climate justice (Jenkins, 2014). Nevertheless, using the words of the economist Dani Rodrik, “[…] the world is – most of the time – a second-best issue.” (Rodrik, 2015): political economy constraints – such as lobbying or low willingness to pay – limits the implementation of such theoretically optimal CERM, suggesting an innovative pursuit of a mix of second-best policy instruments (Jenkins, 2014) such as carbon offsets.

Carbon credits in the voluntary market are supposed to be characterized by five core principles, which are additionality, avoiding overestimation, permanence, exclusive claim, and the provision of additional co-benefits in line with the UN’s SDGs (Broekhoff et al., 2019). The principle of additionality constitutes the basis on which the whole voluntary carbon market is built but may be debatable since they must be built on an alternative scenario to compare with (Broekhoff et al., 2019; Hausfather, 2022; Hodgson, 2022). Indeed, following the principle of additionality, traditional carbon credits are often generated from non-provable alternative scenarios. As a result, carbon credits are generated by comparing them to a non-existing parallel world, a common practice in modeling but controversial when it represents the main mechanism by which such credits are generated (Broekhoff et al., 2019). This issue represents one of the main concerns that should be addressed for carbon credits’ credibility. If a recent investigation into Verra (Greenfield, 2023), the largest carbon offset certifier, proves to be accurate, over 90% of its rainforest carbon offsets may be ineffective and may even exacerbate global warming, raising questions about the use of carbon offsets as a solution to climate change (Gabbatiss et al., 2023; West et al., 2020).

Advancements in carbon footprinting: the role of new technologies

Life cycle assessment (LCA) is a systematic methodology to evaluate the environmental impacts of a product, process, or activity over its entire life cycle, from raw material extraction to disposal. However, LCA studies may fail to account for all possible inputs of a product system, especially for complex and geographically distributed systems such as current global supply chains (Jakobs et al., 2021). Real-time and dynamic data are required but nearly impossible to collect from enterprises that cannot grasp the environmental impact data of the entire life cycle of their products. LCA assessment and evaluation systems and tools are independent and not directly integrated with the existing enterprise information systems. However, technological progress offers new opportunities. For instance, LCA practices can be developed and integrated with other technologies to support highly detailed and real-time analysis of inventory data. Tao et al. provided a multi-layered structure to compute energy savings and emission reduction by integrating LCA with the internet of things (IoT) and bills of materials (BOM) (Tao et al., 2014). Van Capelleveen et al. present the "Footprint of things," a hybrid architecture that takes advantage of a Radio Frequency Identification (RFID) regulated IoT infrastructure to collect real-time, process-specific inventory data, unlike the current averages approach (van Capelleveen et al., 2018). Mishra and Singh propose a framework to allow automated LCA using the above-mentioned technologies to evaluate all CO_2 emissions of each life cycle step to offset them by planting trees. They propose a set of equations to point out all the necessary information for a generic manufacturing product embodied carbon assessment (Mishra and Singh, 2019). Zhang et al. propose an implementation framework regulated by blockchain technology that orchestrates the data flow collected by IoT technologies across various steps of the supply chain, providing a rough estimate of the proposed system’s cost if implemented by a Chinese manufacturing producer (Zhang et al., 2020). The application of blockchain technology in LCA guarantees transparency and traceability, using RFID to provide real-time and accurate data. Recently, multiple authors proposed a carbon credit ecosystem using blockchain technology for transparent and standardized carbon trading (Saraji and Borowczak, 2021; Khaqqi et al., 2018; Fu et al., 2018). However, blockchain is not always needed.

Blockchain is a data structure made up of blocks that, when combined with other critical components, can create a real-world application. It is a mechanism for handling digital data that establishes ownership of tangible and intangible goods and services. Distributed systems are used to give individual parties control, ownership, and creation of digital data that represent ownership of goods and services. The key distinction between past times when distributed technologies had not been invented is that a consensus must be set up and enforced by a trusted third party. With the advent of distributed systems, a single person can now manage and execute tasks that previously necessitated the involvement of a trusted intermediary. Protocol rules are embedded and enforced in each client program to make distributed technologies work. Cryptography and consensus rules are crucial tools to achieve distributed consensus. The timing of data operations shared between distributed nodes is important, especially the order in which data operations occur when two entities exchange a limited digital representation of value within the rules they have agreed upon. The Proof-of-Work (PoW) is one of the most innovative and trustworthy consensus algorithms. PoW attempts to provide clear economic incentives to validators who are forced to invest in validation infrastructure in advance and compete with existing and potential new validators. Other consensus mechanisms exist, but with a different level of trustlessness and network security. A blockchain system’s data structure contains data about ownership in the form of blocks connected on a chain of increasing size. It is well-suited to the validation process and ordering operations on data, but it is heavy, non-scalable, and must be replicated throughout all of a network’s nodes to ensure security and anonymity. By using a different data structure (e.g., a cryptographically signed database), it might be possible to achieve scalability, speed, and less storage space. Proof-of-Stake (PoS) allows for a more efficient use of energy per transaction, as recently reported in the shift from PoW to PoS in the Ethereum system (Yaffe-Bellany, 2022).

Advancements in carbon footprinting: the role of methodologies and communication

Currently both environmentally extended input-output, process-based and hybrid LCA are used for computing carbon footprint, presenting slightly different results (Steubing et al., 2022; Agez et al., 2020). Today efforts concerning the input-output analysis community are mainly focused on identifying a modelling framework capable of representing with greater detail and realism the dynamics governing production processes (Duchin, 2017; Pauliuk et al., 2015a, 2015b). To do this, in addition to working on increasingly higher resolution tables of activities, commodities, regions, etc., numerous efforts are also focused on better accounting for and modelling the dynamics of infrastructure investments and capital goods (i.e., technologies) (Södersten and Lenzen, 2020; Södersten et al., 2018a; O'Mahony et al., 2009). Among the various remarkable works, the recent researches of Södersten and colleagues represent the most advanced effort of extending the classical framework making information for capital expansion explicit proposing methodologies for disaggregating yearly consumption of fixed capital and gross fixed capital formation (Södersten et al., 2018b, Södersten and Lenzen, 2020). Vita et al. adopted IO to investigate the impact associated with the fulfilment of fundamental human needs, as defined by Max-Neef framework (Vita et al., 2019a).

Galindro et al. conducted a literature review to explore the problems associated with communicating LCA results and possible improvements. The review identifies four main issues: the diversity of methodologies, lack of external reference values for comparison, absence of positioning of products among peers, and a lack of understanding of multiple indicators. The uncertainty of data and methodological choices influence results significantly. To address these issues, the introduction of Environmental Product Declarations (EPDs) provides a means of providing quantified and objective information on the environmental burdens of products fulfilling the same need providing a foundational step towards effective result comparisons. However, over 450 environmental labels are active worldwide, making it challenging for consumers and market actors to relate to many environmental labels and reporting initiatives. Therefore, it is necessary to establish a common methodological approach that enables relevant and consistent environmental claims for a single comprehensive assessment. Customers have to face too many, and sometimes misleading, environmental claims (Chan, 2000). In the light of overcoming this obstacle, efforts in this direction have resulted in initiatives such as the EU pilot project Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) (Bach et al., 2018).

2. A novel carbon emission reduction mechanism

A novel individual consumption-based carbon emission reduction mechanism is here presented, called BitCO$_2$. It aims to incentivize individuals to choose less carbon-intensive products and services by using a token system. The mechanism works by creating a positive feedback loop, whereby the individual's choice to consume less carbon-intensive products earns them BitCO$_2$ tokens. These tokens can be thought of as a way to internalize the social cost of carbon into consumer choices, making less carbon-intensive options more affordable and promoting diffusion.

BitCO$_2$ is a new approach to traditional carbon pricing strategies, such as taxes or cap-and-trade systems, which focus on reducing emissions by charging or restricting the activities of producers or emitters. Instead, BitCO$_2$ aims to promote a sustainable and low-carbon economy by encouraging less carbon-intensive consumer choices. This is achieved by creating a market for emission reductions in which individuals can trade their BitCO$_2$ tokens, while businesses can offset their carbon emissions by purchasing these tokens. BitCO$_2$ tackles climate change by increasing the attractiveness of sustainable alternatives, without relying on traditional carbon pricing techniques that may face political and economic obstacles.

2.1. *Fulfilling a need*

Most CERMs focus on producers for practical and economic reasons (World Bank Group; Haites, 2018). However, as most economic models – including those based on Leontief's input-output model (Miller and Blair, 2009) – assume, production takes place triggered by the demand for goods and services of final consumers. In fact, it exists because there are needs of final consumers that can be fulfilled by the consumption of some commodities. Undoubtedly, the production of these commodities involves the activation of certain industrial activities that can release greenhouse gases.

Human beings have a wide range of needs, some of which, for instance the most personal and intimate ones, cannot be satisfied by material goods alone. However, some of these can be directly or – at least – more easily fulfilled through the consumption of certain commodities (e.g., both a heat pump and a gas boiler can deliver heat, directly consuming different commodities, respectively electricity and gas).

For instance, domestic users do not have a need for natural gas. What they do need is to heat their home and the water they use for washing. Both the heat released by burning natural gas and the heat released by a heat pump can be used to heat water. However, these two slightly different commodities require the activation of technologies whose production activity involves different amounts of GHG emissions.

Defining what is meant by a specific need is crucial and potentially critical for this CERM. National accounts and studies in industrial ecology can help define the way (Vita et al., 2019a, 2019b, 2020; Bjelle et al., 2021; Ivanova et al., 2016, 2017). Heating shelters, exploiting electric energy, travelling to point A to point B, eating food, are just examples of the most carbon intensive needs that each of us have. To fully understand and address each need, it is necessary not only to characterize it qualitatively, but also to quantify it. This leads to the definition of a minimum theoretically satisfiable unit of need, similar to the functional unit in LCA.

2.2. *The theme of comparativeness*

The proposed CERM requires to compare specific consumption behavior with the average choice in the precise market in which the consumer is active, defined by the need it serves and limited to a specific geographical and temporal scope. This approach involves calculating the footprint of multiple commodities that can be used to satisfy the same need, determining the difference between their GHG footprint.

Estimates of these GHG emissions are notoriously complex, but a whole branch of Industrial Ecology exists, encompassing methodologies such as environmentally extended input-output analysis and process-based LCA (Steubing et al., 2022; Palazzo et al., 2020). However, even the most accurate estimate of a product's carbon footprint requires assumptions. Even if it were possible to know the exact emissions released by each activity, a method of allocating these impacts would be required when multiple commodities are produced from a single activity (Suh et al., 2010). For example, it may be controversial to allocate the GHG impact of breeding a cow to produce milk and meat on a physical, energy or economic basis (Suh et al., 2010).

In addition, this mechanism allows for a dynamic comparison between what is being consumed at a given point in time and space and how the average of alternatives evolves. As a need becomes decarbonized, the difference between the best and average choice narrows. This approach offers a more objective and flexible way to evaluate the carbon impact of different commodities, adapting to the changing realities of the market and enabling a more accurate comparison between different alternatives over time.

As told, the estimation of footprints involves various assumptions, most notably when the satisfaction of certain needs requires the consumption of other goods, such as specific technologies needed for making need satisfaction less carbon intensive.

2.3. The two steps approach of technological change

Transformations such as the sustainable transition require the introduction of new types of machinery, interventions, or generically innovation in the way inputs are transformed into output (i.e., technology). Such technologies are usually introduced to fulfil a certain necessity – usually already satisfied by a present solution – with the promise of reducing operational impacts (i.e., allowing to perform specific activities that allows to fulfil a specific need with less life cycle GHG emission).

The technology impact assessment required in the proposed CERM is separated into two steps that help in distinguishing between the GHG impact associated with the introduction of the technology (i.e., investment step) and its operation (i.e., operation step).

The distinction between these two steps allows us to separate two important moments in the satisfaction of needs. The purchase by the consumer agent of the capital good needed to reduce the impact of his need and its use. In virtually all cases, the purchase of a capital good leads to increased pressure on the emissions reduction problem (i.e., essentially all products have a positive GHG footprint). The distinction between the two steps permits the determination of a GHG payback time associated with the exploitation of a technology to satisfy a need. In fact, access to a particular capital good in a particular market enables each technology to be compared in terms of GHG emissions which may be more or less than the average. If the investment step (i) GHG footprint is greater than the average, a GHG burden is associated with that technology (e.g., buying an electric car in step (i) to enable the activity – driving the vehicle in the step (o) – satisfying a private transport need. This usually bring a burden of GHG emission with respect to buying a traditional internal combustion engine vehicle (Hoekstra, 2019)) (See Fig. 2).

Whenever a technology that allows a need to be met at a lower-than-average level is employed, the difference between the operational (o) footprint of that specific commodity (e.g., private transport with an electric car charged with renewable electricity) and that of the need (i.e., the weighted average of the footprints of all commodities meeting that need in that market) determines the avoided GHG. If a cumulative amount of GHG is avoided equal to the burden of that technology, then each new use of that technology that produces a lower-than-average commodity generates avoided GHG, calculated as CO_2eq. This avoided impact can be tokenised into a digital carbon credit called BitCO_2, named on the unit of measure of GHG emissions. This token also gives its name to the CERM proposed here.

2.4. Technological characterisitcs

BitCO_2 requires the estimate of GHG footprint of a number of commodities and needs, being the token generated from the difference between two of them. This comes from the understanding that tracking all the flows of GHG is not currently technologically feasible (even using blockchain) and not necessarily needed. Moreover, as explained previously, this approach avoids forcing agents to pay for their additional emissions, instead rewarding them for their low-carbon footprint consumption choices.

The main technology adopted for allowing for a transparent, robust and reproducible estimation of footprint is the use of open-source software and a Structured Query Language (SQL) platform. For every issued token, a link to the methodology, where all the assumptions are explained, source code and data will be provided. The value of the token will be intimately linked with the quality of the research behind the estimations. The main quantitative information associated with this data will be provided in the form of SQL database in which data behind the footprint calculation will be openly available.

The blockchain becomes necessary for the crucial tasks that make it possible to connect the agent responsible for the carbon-avoiding consumption choice and the agent interested in being recognized as the driver of the avoided emissions. In particular, starting from the amount of avoided GHG associated with each purchasable product, the blockchain:

- creates a quantity of BitCO_2 token (i.e., issuance);
- orchestrates the exchange of tokens between agents;
- burns the tokens when the owner agents decided to claim the reduction of GHG for themselves.

Energy and emission savings are fundamental for the case of BitCO_2 due to the relevance of its emission reduction nature driving the whole proposal. For this reason, a PoS consensus algorithm can better serve the requirements of this mechanism.

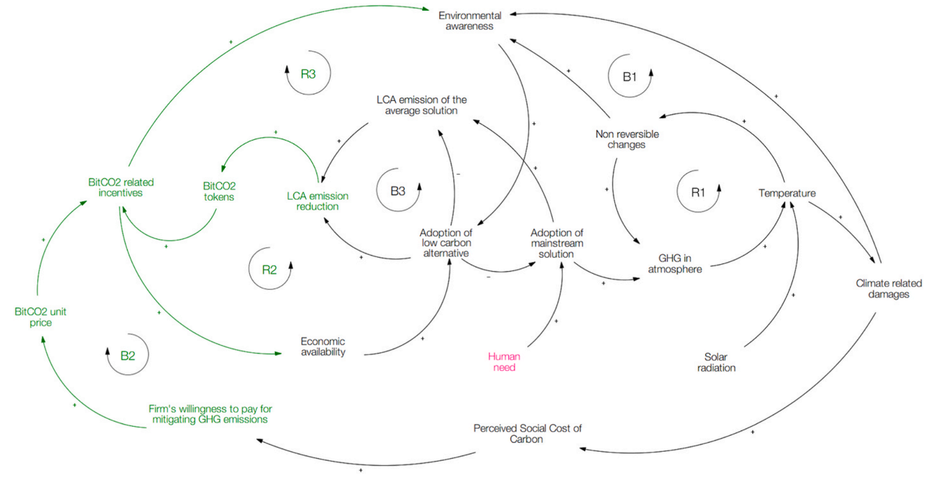

Fig. 2. Causal loop diagram of the proposed carbon emission reduction mechanism, called BitCO_2. The diagram shows a reinforcing loop between the adoption of mainstream solutions and the increase of greenhouse gases (GHG) in the atmosphere, which in turn increases temperature and leads to non-reversible changes that further increase GHG (in black). The increase in temperature also causes climate-related damages, creating environmental awareness and driving the adoption of low-carbon alternatives. The BitCO_2 mechanism creates a positive feedback loop by incentivizing individuals to choose less carbon-intensive products through the use of tokens (in green). This internalizes the social cost of carbon and makes less carbon-intensive options more affordable, promoting diffusion and leading to a reduction in GHG emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Application

3.1. Context of application

The proposed mechanism has been modelled and tested for the Italian automotive sector. In Italy, the purchase of diesel cars faced a peak in 2017 and began to decrease. Sales of petrol vehicles, instead, reached their maximum value in 2019. In 2020 their sales decreased by about 39%, also due to the COVID-19 pandemic (UNRAE, 2020a). Nevertheless, petrol vehicles still detain the lead as the most popular type of vehicle, with a share of 37.8% of total sales in 2020. Electric cars sales in Italy have increased over the last years, reaching in 2022 a market share of +8.6%, quite far from 20-30% observed in the same year in France, UK and Germany (International Trade Administration, 2023). Reducing the total cost ownership by introducing an additional economic incentive for BEV owners may accelerate the adoption rate of this technology and their contribution to global carbon emission reduction.

Considering that the demand for European private transport is not expected to decrease and given the existence of BEV technology which can satisfy the same need while reducing CO_2 emissions, a CERM in this sector could be useful. For this reason, this section aims at simulating the impact of the proposed CERM related to the private transport sector in Italy, one of the largest EU private passenger's car markets. The objective is to test the role of this mechanism in enhancing the adoption of BEV over ICEV, thus reducing global emissions. To prove that the $BitCO_2$ mechanism is self-sustainable and thus effective in reducing overall CO_2 emissions, it has been tested thanks to the developing of a System Dynamics model. This model considers and links the economic agent which is responsible for the emission embodied in the demanded goods and services (i.e., footprints), that are final consumers, with the one that is materially willing to pay for the mitigation of climate-related damages, that are, in this case, insurance companies. Insurance companies are chosen because of their multiple interests and interconnections with the transportation sector. Insurance companies are interacting with final customers by providing them with car insurance. At the same time insurance companies have an economic return from the mitigation of climate changes related events by reducing the risk exposure of their insurance services against damage resulting from extreme climatic events (Armstrong and Ralph, 2020).

3.2. System dynamics within consequential life-cycle assessment

Consequential LCA, is adopted to describe how environmentally relevant physical flows change as a consequence of possible action carried out in the product system. To understand the environmental response to certain decisions, several methods could be applied. The main Consequential LCA modelling approaches take advantage of economic equilibrium, system dynamics, technology choice, and agent-based models (Palazzo et al., 2020). The most suitable model for a specific analysis must be carefully chosen following its purpose. The economic equilibrium approach focuses on market basics like price and quantity via supply-demand interaction at a very aggregated level. While technology choice models optimize multiple markets' technology selections, they lack the crucial temporal dimension for simulating policy and analysing long-term impacts. In contrast, agent-based models and system dynamics meet this need, with the former fitting complex systems with varied agents. However, for our proposed mechanism, an exhaustive interpretation of micro-level stakeholder behaviour is not necessary. Thus, simulating an aggregated stakeholder class within the SD framework sufficiently captures the mechanism's dynamics.

System Dynamics (SD) approach is used for investigating, understanding, modelling, and tackling well-defined endogenous problems concerning physical or conceptual systems that are suitable to be reproduced by means of casual relationships. This is the case of complex issues that consist of feedback mechanisms, delays, and quantitative causal relations between variables.

This approach has been widely adopted in the existing literature about innovation diffusion phenomena, in a particularly large variety of studies on new transportation mode adoption, especially BEV adoption, is based on SD models. This is the case of the work done by Ercan et al. (2016) who used a SD approach to propose possible public transportation policies to be adopted by policymakers or urban planners. Their model is aimed to simulate the most realistic and practical CO_2 mitigation scenarios for U.S. cities by the adoption of public transportation. Another example is provided by the study done by Fong et al. (2009) who demonstrated the capability of SD to serve as a decision-making tool in Malaysia's urban planning process while considering future CO_2 emission trends. A more sophisticated analysis in the same field is performed by Feng et al. (2019) who incorporate fuzzy logic in a SD model to replicate the comparative process that consumers use to decide among alternatives. Their work is aimed to evaluate how feedback and interactions generated by the introduction of social commerce into EV can influence consumers' choices. The same approach has been exploited also in numerous policy assessment studies both at a national and regional scale (Bendor and Ford, 2006) (Shepherd et al., 2012).

The present work intends to replicate the SD approach derived from previous literature examples and to simulate consumers' BEV adoption choices with a specific focus on the impact that the incentive mechanism based on $BitCO_2$ has in terms of new BEV adopters and consequent CO_2 emission reduction.

3.3. Modelling $BitCO_2$ adopting system dynamics

The newly developed SD model aimed at stimulating the mechanism by considering four specific sections:

- BEV adoption
- BEV vs ICEV LCA
- Market mechanisms
- Incentive mechanisms

The interactions among different model section are reported in Fig. 3, where the main causal loops of the mechanism are represented. For the presentation of each specific section a different coulor it is used in the figure.

The conceptualization of the BitCO2 mechanism through the development of a SD model, is done by considering that in 2020 974'328 people bought an Internal Combustion Engine Vehicle (L'auto, 2020b), and assuming that the Italian automotive future sales will behave similarly to what is predicted to happen on the whole European car market from 2020 to 2025 (STATISTA, 2022a). Potential adopters also vary accordingly to a projection about population growth (STATISTA, 2022b). The literature demonstrates that factors influencing the choice between a BEV and a corresponding ICEV are multifaceted (De Rubens et al., 2018; Olson, 2018). However, considerable evidence highlights that aspects related to the total cost of ownership, predominantly dominated by purchase price for BEVs, and infrastructure-related concerns such as range anxiety or prolonged charging times, play pivotal roles (Berkeley et al., 2018; Tarei et al., 2021). According to the model definition, the potential adopters become actual BEV adopters accordingly to the incidence of the three main adoption barriers, as shown in equation (1) where *PP* stands for *Purchase price*, *Rkm* for *Range of km,* and CT for *Charging time*. Each variable represents the consumers' willingness to buy a medium-sized BEV over a corresponding ICEV considering different prices range (Marigo et al., 2017), vehicle range in km (STATISTA, 2022c), and charging time (Deloitte, 2020). These factors are assumed to vary with respect to the purchase price, the vehicle range and charging time respectively according to a multiple step function derived from literature findings (Marigo et al., 2017)

$$Adoption\ fraction = PP^{\epsilon-price} \bullet Rkm^{\gamma-range} \bullet CT^{\vartheta-charging} \tag{1}$$

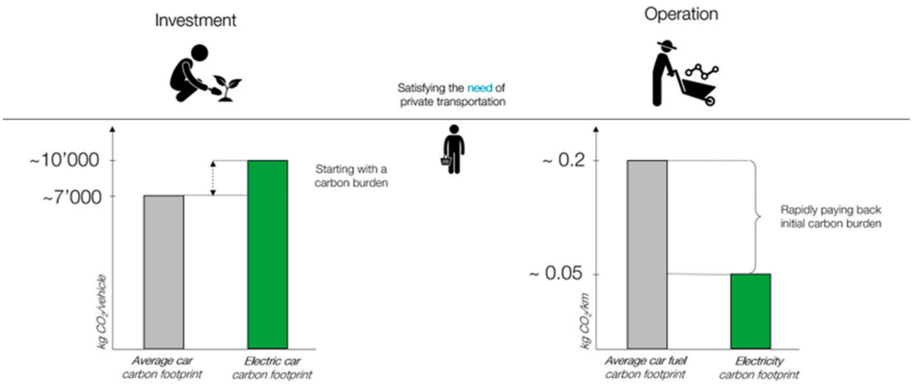

Fig. 3. Visual explanation of investment and operation step within the fulfillment of the need of private transportation considered in the proposed CERM.

The exponential terms of equation (1), namely ϵ_price γ_range $\vartheta\_charging$ represent which is the relative weight Italian citizen give to each of the three previously mentioned factor when they have to choose whether to buy or not a BEV. Equation (1) drives the BEV adoption mechanisms and the adopters convinced to buy an electric vehicle benefit from the emission of the tokens.

To quantify and therefore tokenize the avoided emissions embedded in purchasing and driving a BEV with respect to a similar ICEV, LCA analysis is carried out for both vehicle types. This analysis comprises the emission released during the manufacture and end-of-life of the vehicle (investment step) and those related to the fuel-cycle, i.e. GHG related to the fuel production and direct emission attributable to the operation (operational step). The manufacturing carbon footprint adopted in this case study is characterized by the data taken from existing literature (European Environment Agency, 2018a; Both and Steinfort, 2020a). More in detail, the operational impact of the ICEV is 221.7 $grCO_2/km$, where Well-To-Tank (WTT) emissions are 44.6 $grCO_2/km$ (Prussi et al., 2020a), Tank-To-Wheel (TTW) are 177.1 $grCO_2/km$ (Prussi et al., 2020b). To make the calculations, it is assumed that the heating value of diesel is 34.9 MJ/l (Prussi et al., 2020b) and the fuel consumption of an average diesel middle-size car could be approximated to 6.7 l/100 km (Natural Resources Canada, 2018a). On the contrary, the impact of electric car use is determined by considering how electricity is produced. The electricity mix that is used as reference is the European one, and the corresponding GHG emission were 447 $grCO_2/kWh$ in 2013 (Moro and Lonza, 2018), and 396 $grCO_2/kWh$ in 2016 (Prussi et al., 2020b). As a reference for the 2030 electricity mix, it is used the one defined by IEA in their New Policies Scenario (now Stated Policies Scenario) the same expectations are considered also by JRC (Prussi et al., 2020b). This scenario assumes the emission to be 257 $grCO_2/kWh$ in 2030. This shows how the electricity is expected to become greener along the years. The same value for the years from 2030 to 2040 was projected with a linear regression. Then, by using a conversion factor equal to 16.1 kWh/100 km (Hoekstra, 2019), the amount of grCO2/km emitted by a BEV is found.

Given that a BEV causes more emissions with respect to a ICEV for its manufacturing and disposal but allows to save emissions during the driving cycle, it is possible to determine how many km a BEV adopters must drive before reaching the same total GHG emissions. Once additional manufacturing and dismantling emissions are paid back, the BEV owners sees BitCO2 tokens accredited each time they recharge their cars. These tokens, can be in turn withdrawn by insurance companies in the following years. In this way, guaranteed that the corrisponding emission has been avoided the insurance companies can attribute a discount on the premium tariff for clients in proportion to the $BitCO_2$ they decide to sell them. Generally speaking non all BEV owners may be insured. Therefore, they are given the choice of selling the $BitCO_2$ in the dedicated market where other individuals and firms who are interested can buy them. In this way two markets are formed: the first one exists between car owners and insured people, the second one represents the exchange of BitCO2 among insured people and insurance companies.

The first market is simulated to occur every three months. The dimension of the supply side of the market is subject to the quantity of BitCO2 possessed by car owners. The demand is assumed as a linear function, characterized by two maximum values:

- the maximum quantity of tokens that insured people is willing to purchase at a price equal to 0. It is assumed to be about five times larger than the quantity of BitCO2 emitted in the previous three months.
- the maximum price at which insured people are not willing to buy any token corresponds to the discount that the firm set in the second market.

Both the supply and the demand of this first market are now defined, and their encounter characterizes the price at which the token is sold. Insured people thus can buy the token at the price determined as in Fig. 4 every three months.

The choice of whether to sell or not the BitCO2 to an insurance company is taken by comparing the price at which they purchased the token with the one decided and adopted by insurance agents when they finally collect and burn the tokens. This second market is therefore characterized as in Fig. 5, where the step function is made upon the token prices of the first market.

Insurance companies intend to withdraw the tokens because it means that a certain quantity of CO2 is avoided, and therefore, in the long run, they will pay less to compensate for climate change damages. The discount per token is set by the insurance agents each year and is computed by dividing the revenues that the insurance company has earned during the previous year by all the BitCO2 present in the market. The revenues of the company correspond to the future money-saving that will interest the company itself, due to GHG emissions that have been avoided thanks to the mechanism implemented, and the corresponding avoided damages. Recognizing the complexities involved in quantifying the long-term damages resulting from greenhouse gas emissions and their effects on specific areas, the Social Cost of Carbon (SCC) approach, with its comprehensive assessment of the economic impacts of greenhouse gas emissions, emerges as one of the most robust frameworks for addressing this multifaceted challenge. The BitCO2 pricing structure aligns with the SCC, allowing the market to reflect the trade-off between present emissions and their associated potential future impacts, while considering the uncertainties through sensitivity analyses. The revenues are therefore computed considering the SCC of Italy, 9.22 €/tonCO2 (Ricke et al., 2018). Overall revenues for each ton of CO2 avoided are computed by multiplying the given SCC times the fraction of insured damages. The economic advantage that car owners receive from the choice to buy a BEV is to gain BitCO2 and resell them to the insurance's clients. This determines a monetary flow of revenues that last the whole lifetime of

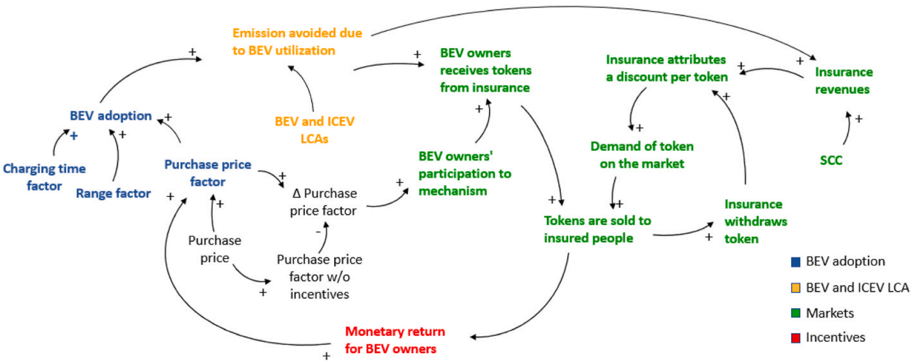

Fig. 4. Causal loop diagram describing the BitCO$_2$ mechanism in the context of its application in the private transportation sector.

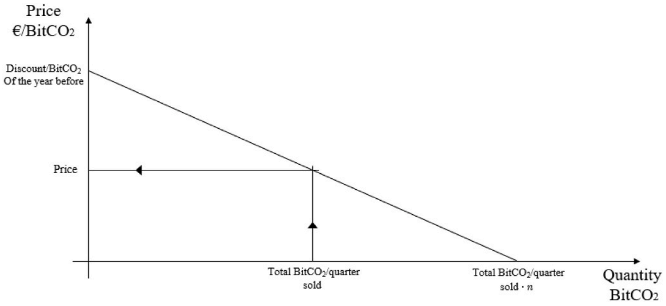

Fig. 5. First market mechanism.

their car and act as an incentive by influencing the choice of the type of vehicle at the time of purchase. Thanks to the proposed mechanism the total cost of ownership is expected to reduce accordingly to the number of tokens the driver is going to earn along the BEV lifetime.

4. Results

4.1. Main results

According to the analysis results, in the first period of the simulation horizon, the number of km to reach the parity is equal to 27’770 km, then these variable experiences a decreasing behaviour because the electricity necessary to recharge a BEV is expected to become greener over the years, so the quantity of gCO2 produced to drive one km should reduce. At the end of the policy time horizon, this variable reaches the value of 23’530 km. The difference between the number of BEVs that reach the emission parity in the scenario with the incentive and the ones in the scenario without it represents the number of people that decide to choose to buy and drive a BEV over an ICEV thanks to the economic incentive embedded in BitCO$_2$. These cars are represented in the variable *BEV attracted* which trend is reported in Fig. 6. The owners of such cars are involved in the BitCO2 market-based mechanism and they reach a maximum of around 40 thousand people after the 10th year of the mechanism.

Overall CO$_2$ emissions reduction achieved thanks to BitCO$_2$ mechanism implementation is about 970 ktonCO$_2$eq over 20 years of operation. Starting from the variable *Total actual BitCO2/quarter* and crossing the demand of insured people with the supply of cars owners, the price of the token is defined, and it resulted to vary between 6.4 and 2.4 €/BitCO$_2$ over the simulation horizon.

In the end, the incentive for future BEV owners is computed considering the price of the token earned during the lifetime of the car, discounted to the year of purchase of the vehicle. As already shown, this incentive is then decurted from the variable *Purchase price*, which represents one of the main barriers to the adoption of a BEV.

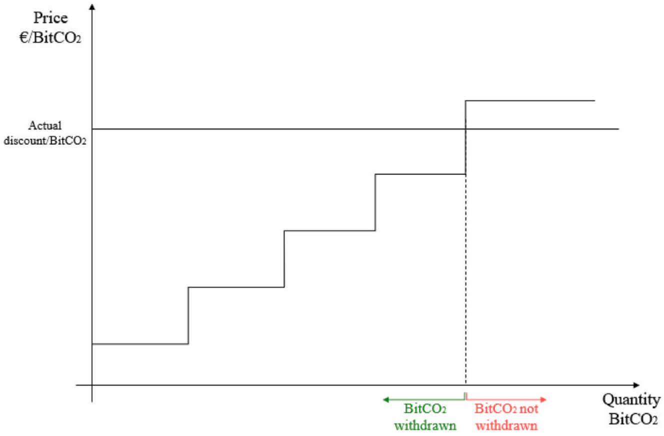

Fig. 6. Second market mechanism.

4.2. Sensitivity analysis

Sensitivity analysis is an important tool to test the robustness of the model’s results subject to the variation of input parameters within their range of possible variation. According to System Dynamic theory, comprehensive sensitivity analysis is generally impossible and especially in the case of significantly non-linear models like the one presented in this work. Indeed, the impact of combination of the assumptions may not be the sum of the impacts of the assumptions in isolation. Therefore, sensitivity analysis must be executed on variables that are both highly uncertain and likely to be influential (Ricke et al., 2018). One of common methods is to define best- and worst-case scenario defining a plausible range for the most likely influential variables. The ranges of possible variation are defined through scientific articles and web research. The values’ ranges are reported in Table 1. Then, performing sensitivity analysis on each parameter, *worst* and *best* values are identified to give the least/most favourable outcome, in terms of total avoided emissions.

Note that not all the parameters’ range extremes coincide with *worst* and *best* values. That is the case with BEV purchase price. On the one hand, if the price of the BEV is too low, the role of BitCO$_2$ is not relevant in driving consumer choice; on the other hand, if the price of BEV is too high, the maximum assumed SSC cannot make the choice convenient.

Therefore, *worst* and *best* values fall within range extremes. The outcomes are in line with what is expected: in the *worst* scenario the adoption fraction is the lowest and the difference with the one generated without the incentive is small, leading to engaging few people. As a consequence, a tiny amount of emissions are avoided: 68.9 ktonCO2 (−93% with respect to the base case) at the end of the time horizon. On the contrary, applying the values that give the most favourable scenario, the output of the model shows a huge growth in the adoption fraction

Table 1
Sensitivity analysis values.

	Range	*worst*	*best*	Unit	Source
Charging time	139–289	289	139	Min	Electric Vehicle Database (2022)
Range of km	140–425	140	425	km	Netherlands Enterprise Agency (2021a)
Purchase price	26’000–42’000	31’111	32’222	€	Netherlands Enterprise Agency (2021b)
Mileage	150’000–250’000	150’000	250’000	km	European Environment Agency (2018b)
km/year driven	800–1’117	800	1’011	km	Scognamiglio et al. (2019)
Sales prediction	1’553’988–1’798’541	1’553’988	1’798’540	cars	Piazza (2020)
g_{CO_2}/km ICE	218–228	218	228	gCO2/km	Natural Resources Canada (2018b)
CO2/ICE	5–7.4	7.4	5	ton/vehicle	MIN: (Both and Steinfort, 2020b) MAX: (Ricardo, 2020a)
CO2/BEV	8–14	14	11.33	ton/vehicle	Both and Steinfort (2020b)
g_{CO_2}/km BEV	45–65	65	45	gCO2/km	MIN: (Bieker, 2021) MAX: (Ricardo, 2020b)
Social Cost of Carbon (SCC)	2.13–22.3	2.13	22.30	€	Ricke et al. (2018)
Fraction of insured damages	0.36–0.447	0.36	0.44	–	Swiss Re Institute (2020)

due to the higher incentive and less stringent barriers. Hence, the number of people that decide to fulfil their need with a less carbon-intensive alternative increases the BEV purchased thanks to the policy discount reaches a value of 189’000 cars. This means that the insurance generates a higher number of tokens, which implies avoiding more emissions. In this case, the market mechanism begins earlier, driven by scenarios’ assumption on electricity’s carbon intensity reduction, and the BitCO2 assumes high prices due to the huge values of the discount set by the firm. Despite the high costs that the insurance must pay, the SSC is so high (around 22 €/ton) that the revenues overcome expenses, generating profit. In the end, the CERM results were more effective: a total of 5’240 ktonCO2 are avoided, +440% with respect to the base case. Figs. 7 and 8 shows the results for sensitivity analysis, the base case is reported in red while *best* and *worst* scenarios are reported in sky-blue and red respectively (see Fig. 9).

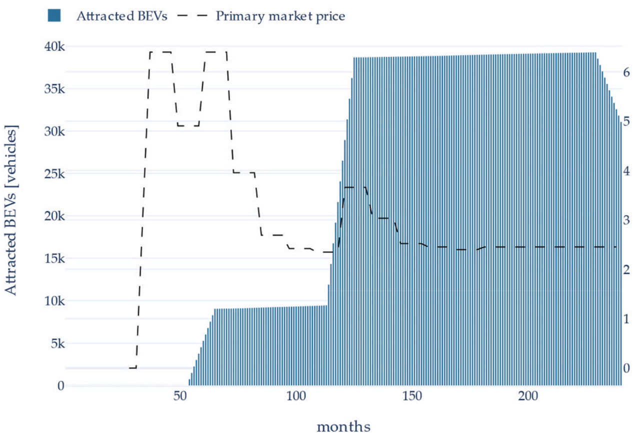

Fig. 7. Number of additional BEVs purchased thanks to the $BitCO_2$ mechanism and price of $BitCO_2$ tokens by month.

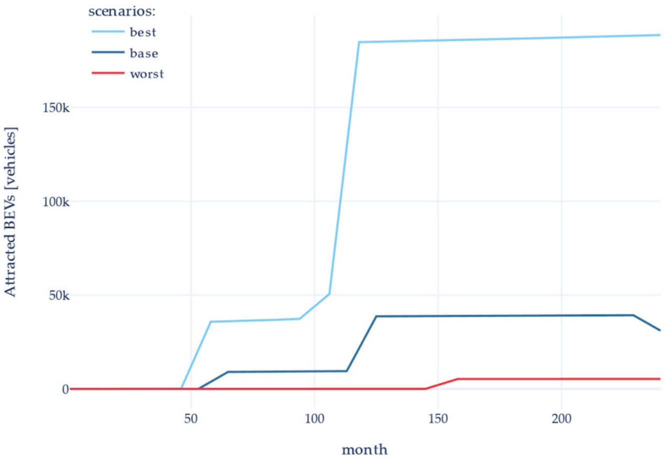

Fig. 8. Number of BEV attracted by scenario and month.

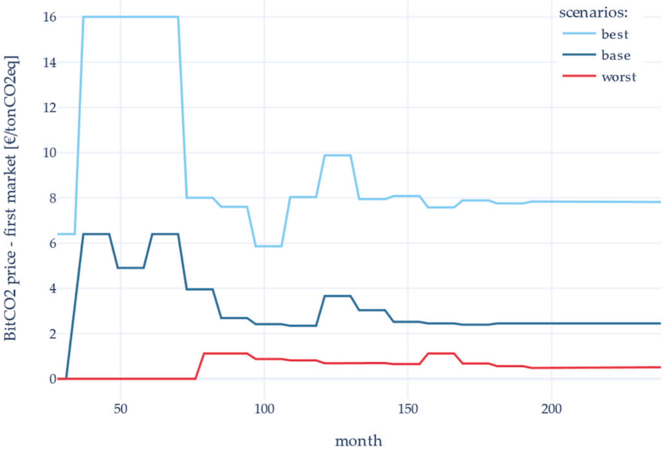

Fig. 9. BitCO2 price by scenario and month.

5. Conclusion and policy implications

Today the European Union Emission Trading System (EU-ETS) is a rather complex market scheme, importantly regulated by ancillary entities such as Market Stability Reserved (MSR). MSR played a crucial role in the recent downturn of the price of EU-ETS allowances, keeping the price at a pre-pandemic level disregarding the impact that COVID-19 had on production and consumption (Azarova and Mier, 2021). Following this period, the price of EU-ETS allowance has only grown, disregarding the consequence of the February 2022 Russian invasion of Ukraine. Now the price is around 80 €/ton, very close to all-time high (i.e., about 100 €/ton).

A carbon tax directly sets a price on carbon by defining an explicit tax rate on GHG emissions or—more frequently—on the carbon content of fossil fuels. It is different from an ETS in that the emission volume of a carbon tax is not pre-defined while the carbon price is.

Sweden introduced the first ever carbon pricing initiative at the national level, in 1991 and today is the country that prices carbon at the highest levels (i.e., 140 $/ton) (Haites, 2018). Virtually all carbon pricing mechanisms are based on a PBA approach, that considers only those emissions produced within the jurisdiction boundaries. In fact, the effective implementation of CBA-based carbon pricing mechanisms represents a difficult technical and socio-political challenge. Nevertheless, Sweden, a climate policy pioneer, has recently proposed the first political initiative in this direction defining for the first time a CBA carbon emissions target, with the country aiming to hit net zero by 2045 (THE LOCAL se, 2022). As anticipated the EU is working on the implementation of the Carbon-Boarder Adjustments mechanism, gradually implementing it to properly face multiple technical and political issues. Importers will have to report emissions embedded in their goods without paying a financial adjustment in a transitional phase starting in 2023, giving time to reach full operation in 2026 (European Commission, 2021). Carbon pricing initiatives acting at the national or supranational level can target a large amount of carbon emission. However, their complexity and extension can limit the pace of implementation of mechanism improvements.

Human activities, such as burning fossil fuels for electricity generation, heating, and transport, are the primary drivers of a large amount of GHG emissions. That's why active and willing participation of citizens in combatting climate change may be pivotal to address this issue (IEA. Net, 2021). Thus, promoting sustainable development through less carbon intensive behaviour might be at the centre of policy makers' agenda to fight climate change through a just energy transition.

In this paper an innovative carbon emission reduction mechanism is presented and its efficacy in decreasing the current carbon emissions of the Italian private road transport sector tested. The process is founded on a consumption-based emission accounting method. System Dynamics is selected as the most suited modelling approach for testing the novel mechanisms here proposed. The role of consumers is a key factor in the mechanism: it ultimately relies upon the fact that they may choose to adopt a less carbon-intensive lifestyle, which is exemplified by the choice of the BEV over the ICEV. The decision, in this case, is promoted through incentives. The market-based mechanism comprises a BEV adoption model. It considers the three most relevant limiting barriers in the decision that a potential adopter must face: BEV range limitation, its charging time, and its high purchase price. Then the environmental implication of the vehicle choice is studied through the LCA of BEV and ICEV, which include both the emissions that are released during vehicle manufactory and the emission owing to the operational phase (well to wheel fuel assessment).

When people choose to purchase a BEV and they participate in the BitCO$_2$ market, they gain a monetary return. The incentive is supplied by any agent interest in reducing GHG emissions, in this case insurance companies. In fact, they have an interest in decreasing GHG emission release into the atmosphere since it would also imply reducing the intensity and the frequency of future climate change damages they will eventually have to pay for.

The total quantity of emissions avoided due to the implemented mechanism during the 20 years of the policy is 973 ktonCO$_2$eq. It has to be taken into account that the yearly GHG emission in Italy is around 330 MtonCO$_2$eq (STATISTA, 2022d). From this perspective, the mechanism does not seem to attain a great achievement. The cause is probably the modest amount of people that chose the BEV due to the policy incentives, about 40 thousand people, thus making the participation in the market mechanism limited. The reason behind this phenomenon is the small economic incentive. The price attributed to the token in the markets can be identified as the bottleneck of the model: if the prices (and so the incentive) is not attractive, people are not motivated in taking part in the mechanism. The economic value is strictly related to the discount imposed by the insurance, which is linked to the social cost of carbon. The considered social cost of carbon is associated just with the climate change damages that occur inside Italian borders due to the emission of an additional tonne of CO2. However, the changes in climate due to the GHG are not related to where emissions are generated or avoided. Therefore, in this case, the Italian social cost of carbon does not consider the damages prevented outside Italy thanks to the policy. This can be considered as a future improvement of the current work. The variation of the value related to the social cost of carbon is the key to having a different economic incentive. Moreover, the model can be replicated in terms of the sectors considered. Analysing other economic sectors would be possible. For what regards the food sector, greener substitutes can be represented by plant-based meet as the alternative to beef;for the power sector, footprints of electricity produced mostly by renewable sources instead that generated mainly by fossil fuel could be compared. The BitCO$_2$ mechanism shows promising potential to incentivize carbon-conscious consumer choices.

However, certain limitations of the mechanisms warrant attention. While the proposed CERM is in line with the principles of consumption-based accounting, it is distinctly different from the carbon border adjustment mechanisms under discussion at the European level. Instead, the BitCO$_2$ approach fits seamlessly into the existing voluntary market framework. Unlike the tradable carbon credits that are prevalent in the market, the tokens generated by this mechanism are exclusive to end users who have the discretion to engage in trading. This mechanism could crossover with other parallel initiatives at national and international level, particularly in the automotive sector. This aspect may place some constraints on the acceptability of the mechanism, but it also places it in a distinct dimension compared to the current landscape of national or supranational commitments, directly interacting with final consumers. The effectiveness of this mechanism will in practice depend on the credibility and transparency of the calculations underlying the generation of tokens.

Consequently, the reliability and transparency of data become paramount. This, too, can be regarded as a limitation, considering the unavoidable existing uncertainty and subjectivity in estimating the carbon footprint of certain products. Regulations at national and international level may mitigate this aspect.

Furthermore, the mechanism will inherently need to consider the users' potential to exploit the incentives. There is a risk that this could lead to over-consumption, which would undermine the effectiveness of the mechanism. Countermeasures to address these concerns will need to be carefully devised.

CRediT authorship contribution statement

Nicolò Golinucci: Formal analysis, Literature review analysis, Conceptualization, and formalization of the modelling framework; Case study preparation, Visualization, Writing – original draft. **Francesco Tonini:** Formal analysis, Literature review analysis, Formalization of the modelling framework, Case study preparation, Visualization, Writing – original draft. **Matteo Vincenzo Rocco:** Conceptualization, and formalization of the modelling framework, Writing – review & editing, Writing – original draft, final draft, Supervision. **Emanuela Colombo:** Writing – review & editing, Writing – original draft, final draft, Supervision, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nicolo Golinucci reports a relationship with eNextGen that includes: board membership. Francesco Tonini reports a relationship with eNextGen that includes: non-financial support.

Data availability

Data will be made available on request.

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References

Afionis, S., Sakai, M., Scott, K., Barrett, J., Gouldson, A., 2017. Consumption-based carbon accounting: does it have a future? Wiley Interdiscip Rev Clim Change 8, 1–19. https://doi.org/10.1002/wcc.438.

Agez, M., Wood, R., Margni, M., Strømman, A.H., Samson, R., Majeau-Bettez, G., 2020. Hybridization of complete PLCA and MRIO databases for a comprehensive product system coverage. J. Ind. Ecol. 24, 774–790. https://doi.org/10.1111/jiec.12979.

Armstrong, R., Ralph, O., 2020. Climate Change: Can the Insurance Industry Afford the Rising Flood Risk? Financial Times.

Auerbach, A.J., Keen, M., Vella, J., 2017. Destination-based cash flow taxation. SSRN Electron. J. https://doi.org/10.2139/ssrn.2908158.

Azarova, V., Mier, M., 2021. Market Stability Reserve under exogenous shock: the case of COVID-19 pandemic. Appl. Energy 283, 116351. https://doi.org/10.1016/j.apenergy.2020.116351.

Bach, V., Lehmann, A., Görmer, M., Finkbeiner, M., 2018. Product environmental footprint (PEF) pilot phase-comparability over flexibility? Sustainability 10. https://doi.org/10.3390/su10082898.

Bendor, T., Ford, A., 2006. Simulating a combination of feebates and scrappage incentives to reduce automobile emissions. Energy 31, 1197–1214. https://doi.org/10.1016/j.energy.2005.05.024.

Berkeley, N., Jarvis, D., Jones, A., 2018. Analysing the take up of battery electric vehicles: an investigation of barriers amongst drivers in the UK. Transp Res D Transp Environ 63, 466–481. https://doi.org/10.1016/j.trd.2018.06.016.

Bieker, G., 2021. A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars.

Bjelle, E.L., Wiebe, K.S., Többen, J., Tisserant, A., Ivanova, D., Vita, G., et al., 2021. Future changes in consumption: the income effect on greenhouse gas emissions. Energy Econ. 95, 105114 https://doi.org/10.1016/j.eneco.2021.105114.

Both, D., Steinfort, T., 2020a. Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector. Frontier Economics Ltd.

Both, D., Steinfort, T., 2020b. Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector. Frontier Economics Ltd.

Breetz, H., Mildenberger, M., Stokes, L., 2018. The political logics of clean energy transitions. Bus. Polit. 20, 492–522. https://doi.org/10.1017/bap.2018.14.

Broekhoff, D., Gillenwater, M., Colbert-Sangree, T., Cage, P., 2019. Securing Cimate Benefit: A Guide to Using Carbon Offsets.

Chan, R.Y.K., 2000. The effectiveness of environmental advertising: the role of claim type and the source country green image. Int. J. Advert. 19, 349–375. https://doi.org/10.1080/02650487.2000.11104806.

Colgan, J.D., Green, J.F., Hale, T.N., 2021. Asset revaluation and the existential politics of climate change. Int. Organ. 75, 586–610. https://doi.org/10.1017/S0020818320000296.

De Rubens, G.Z., Noel, L., Sovacool, B.K., 2018. Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale. Nat. Energy 3, 501–507. https://doi.org/10.1038/s41560-018-0152-x.

Deloitte, 2020. To Learn More about the Global Automotive Consumer Study, vol. 28.

Dietzenbacher, E., Cazcarro, I., Arto, I., 2020. Towards a more effective climate policy on international trade. Nat. Commun. 11, 1–12. https://doi.org/10.1038/s41467-020-14837-5.

Duchin, F., 2017. Resources for sustainable economic development: a framework for evaluating infrastructure system alternatives. Sustainability 9, 2105. https://doi.org/10.3390/su9112105.

Electric Vehicle Database, 2022. Electric Vehicle Database.

Ercan, T., Onat, N.C., Tatari, O., 2016. Investigating carbon footprint reduction potential of public transportation in United States: a system dynamics approach. J. Clean. Prod. 133, 1260–1276. https://doi.org/10.1016/j.jclepro.2016.06.051.

European Commission, 2021. Carbon Border Adjustment Mechanism: Questions and Answers. An Official Website of the European Union. https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661.

European Environment Agency, 2016. Trends and Projections in the EU ETS in. https://doi.org/10.2800/472636, 2016.

European Environment Agency, 2018a. Electric Vehicles from Life Cycle and Circular Economy Perspectives: TERM 2018: Transport and Environment Reporting Mechanism (TERM) Report.

European Environment Agency, 2018b. Electric Vehicles from Life Cycle and Circular Economy Perspectives: TERM 2018: Transport and Environment Reporting Mechanism (TERM) Report.

Feng, B., Ye, Q., Collins, B.J., 2019. A dynamic model of electric vehicle adoption: the role of social commerce in new transportation. Inf. Manag. 56, 196–212. https://doi.org/10.1016/j.im.2018.05.004.

Fischer-Kowalski, M., Weisz, H., 1999. Society as a hybrid between material and symbolic realms. Toward a theoretical framework of society-nature interaction. Adv. Hum. Ecol. 8, 215–251.

Fong, W.K., Matsumoto, H., Lun, Y.F., 2009. Application of System Dynamics model as decision making tool in urban planning process toward stabilizing carbon dioxide emissions from cities. Build. Environ. 44, 1528–1537. https://doi.org/10.1016/j.buildenv.2008.07.010.

Fu, B., Shu, Z., Liu, X., 2018. Blockchain enhanced emission trading framework in fashion apparel manufacturing industry. Sustainability 10, 1–19. https://doi.org/10.3390/su10041105.

Gabbatiss, J., Dunne, D., Chandrasekhar, A., Dwyer, O., Lempriere, M., Quiroz, Y., Tandon, A., Viglione, G., 2023, September. 25). In-depth Q&A: Can ‘carbon offsets’ help to tackle climate change? Carbon Brief.

Green, J.F., 2021. Does carbon pricing reduce emissions? A review of ex-post analyses. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/abdae9.

Greenfield, P., 2023. Revealed: More than 90% of Rainforest Carbon Offsets by Biggest Certifier Are Worthless, Analysis Shows. The Guardian.

Haites, E., 2018. Carbon taxes and greenhouse gas emissions trading systems: what have we learned? Clim. Pol. 18, 955–966. https://doi.org/10.1080/14693062.2018.1492897.

Hausfather, Z., 2022. Let’s not pretend planting trees is a permanent climate solution. N. Y. Times 1–2.

Hodgson, C., 2022. Companies Used Carbon Credits Created in Oil Extraction Projects. Financial Times.

Hoekstra, A., 2019. The underestimated potential of battery electric vehicles to reduce emissions. Joule 3, 1412–1414. https://doi.org/10.1016/j.joule.2019.06.002.

IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, Paris https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach, License: CC BY 4.0.

IEA. Net, 2021. Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, p. 224.

IEA. World, 2022. Energy Outlook, p. 2022.

International Trade Administration. Italy automotive electric vehicles. https://www.trade.gov/market-intelligence/italy-automotive-electric-vehicles.

IRENA, 2022. Renewable Power Generation Costs in 2021.

Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., et al., 2016. Environmental impact assessment of household consumption. J. Ind. Ecol. 20, 526–536. https://doi.org/10.1111/jiec.12371.

Ivanova, D., Vita, G., Steen-Olsen, K., Stadler, K., Melo, P.C., Wood, R., et al., 2017. Mapping the carbon footprint of EU regions. Environ. Res. Lett. 12 https://doi.org/10.1088/1748-9326/aa6da9.

Jakob, M., Steckel, J.C., Edenhofer, O., 2014. Consumption- versus production-based emission policies. Annu Rev Resour Economics 6, 297–318. https://doi.org/10.1146/annurev-resource-100913-012342.

Jakob, M., Ward, H., Steckel, J.C., 2021. Sharing responsibility for trade-related emissions based on economic benefits. Global Environ. Change 66, 102207. https://doi.org/10.1016/j.gloenvcha.2020.102207.

Jakobs, A., Schulte, S., Pauliuk, S., 2021. Price variance in hybrid-LCA leads to significant uncertainty in carbon footprints. Frontiers in Sustainability 2. https://doi.org/10.3389/frsus.2021.666209.

Jenkins, J.D., 2014. Political economy constraints on carbon pricing policies: what are the implications for economic efficiency, environmental efficacy, and climate policy design? Energy Pol. 69, 467–477. https://doi.org/10.1016/j.enpol.2014.02.003.

Khaqqi, K.N., Sikorski, J.J., Hadinoto, K., Kraft, M., 2018. Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application. Appl. Energy 209, 8–19. https://doi.org/10.1016/j.apenergy.2017.10.070.

Liu, Z., Deng, Z., Davis, S., Ciais, P., 2023. Monitoring global carbon emissions in 2022. Nat. Rev. Earth Environ. https://doi.org/10.1038/s43017-023-00406-z.

L’auto, U.N.R.A.E., 2020a. Sintesi Statistica. 2020.

L’auto, U.N.R.A.E., 2020b. Sintesi Statistica. 2020.

Marigo, F., Melograna, F., Busi, F., Candon, C., 2017. Indagine di mercato Nissan sulle auto elettriche 2017. Nissan Motor Corporation.

Mildenberger, M., Lachapelle, E., Harrison, K., Stadelmann-steffen, I., 2021. Limited impacts of carbon tax rebate programmes on public support for carbon pricing. Nat. Clim. Change. https://doi.org/10.1038/s41558-021-01268-3.

Miller, R.E., Blair, P.D., 2009. Input-output Analysis: Foundations and Extensions. Cambridge University Press.

Mishra, S., Singh, S.P., 2019. Carbon management framework for sustainable manufacturing using life cycle assessment, IoT and carbon sequestration. Benchmarking. https://doi.org/10.1108/BIJ-01-2019-0044.

Mock, P., Tietge, U., 2022. Germany, Not the Land of Compact Cars: Why the EU New Car CO2 Standards Are Nothing to Fear. The International Council on Clean Transporation. https://theicct.org/eu-co2-standards-nothing-to-fear-feb22/.

Moro, A., Lonza, L., 2018. Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles. Transp Res D Transp Environ 64, 5–14. https://doi.org/10.1016/j.trd.2017.07.012.

Natural Resources Canada, 2018a. Fuel Consumption Guide, vols. 1–39. Government of Canada.

Natural Resources Canada, 2018b. Fuel Consumption Guide. Government of Canada, pp. 1–39.

Netherlands Enterprise Agency, 2021a. Electric Vehicles Statistics in the Netherlands.

Netherlands Enterprise Agency, 2021b. Electric Vehicles Statistics in the Netherlands.

Olson, E.L., 2018. Lead market learning in the development and diffusion of electric vehicles. J. Clean. Prod. 172, 3279–3288. https://doi.org/10.1016/j.jclepro.2017.10.318.

O’Mahony, M., Timmer, M.P., 2009. Output, input and productivity measures at the industry level: the EU KLEMS database. Econ. J. 119, 374–403. https://doi.org/10.1111/j.1468-0297.2009.02280.x.

Palazzo, J., Geyer, R., Suh, S., 2020. A review of methods for characterizing the environmental consequences of actions in life cycle assessment. J. Ind. Ecol. 1–15. https://doi.org/10.1111/jiec.12983.

Pauliuk, S., Hertwich, E.G., 2015. Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. Ecol. Econ. 119, 83–93. https://doi.org/10.1016/j.ecolecon.2015.08.012.

Pauliuk, S., Majeau-Bettez, G., Mutel, C.L., Steubing, B., Stadler, K., 2015a. Lifting industrial ecology modeling to a new level of quality and transparency: a call for more transparent publications and a collaborative open source software framework. J. Ind. Ecol. 19, 937–949. https://doi.org/10.1111/jiec.12316.

Pauliuk, S., Majeau-Bettez, G., Müller, D.B., 2015b. A general system structure and accounting framework for socioeconomic metabolism. J. Ind. Ecol. 19, 728–741. https://doi.org/10.1111/jiec.12306.

Piazza, F., 2020. New Passenger Car Registrations by Alternative Fuel Type in the European Union. European Automobile Manufacturers Association, p. 6, 2020.

Pindyck, R.S., 2017. Coase lecture—taxes, targets and the social cost of carbon. Economica 84, 345–364. https://doi.org/10.1111/ecca.12243.

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., Lonza, L., 2020a. JEC Well-To-Tank Report V5. https://doi.org/10.2760/959137.

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., Lonza, L., 2020b. JEC Well-To-Tank Report V5. https://doi.org/10.2760/959137.

Ricardo, 2020a. Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles through LCA. European Commission.

Ricardo, 2020b. Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles through LCA. European Commission.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). Earth beyond six of nine planetary boundaries. *Science Advances*. https://www.science.org.

Ricke, K., Drouet, L., Caldeira, K., Tavoni, M., 2018. Country-level social cost of carbon. Nat. Clim. Change 8, 895–900. https://doi.org/10.1038/s41558-018-0282-y.

Rocco, M.V., Golinucci, N., Ronco, S., Colombo, E., 2020. Fighting carbon leakage through Consumption-Based carbon emissions policies: empirical analysis based on the World Trade Model with Bilateral Trades. Appl. Energy. https://doi.org/10.1016/j.apenergy.2020.115301.

Rodrik, D., 2015. Economics Rules: the Rights and Wrongs of the Dismal Science.

Saraji, S., Borowczak, M., 2021. A blockchain-based carbon credit ecosystem. White Paper 1–7.

Scognamiglio, G., Assicurazioni, U., Stampa, S.P.A.C., 2019. Risultati Dell'Osservatorio Unipolsai Sulle Abitudini Di Guida Degli Italiani Nel 2018 in Seguito All'Analisi Dei Dati Delle Scatole Nere Installate Nelle Automobili.

Shepherd, S., Bonsall, P., Harrison, G., 2012. Factors affecting future demand for electric vehicles: a model based study. Transport Pol. 20, 62–74. https://doi.org/10.1016/j.tranpol.2011.12.006.

Södersten, C.J.H., Wood, R., Hertwich, E.G., 2018a. Endogenizing capital in MRIO models: the implications for consumption-based accounting. Environ. Sci. Technol. 52, 13250–13259. https://doi.org/10.1021/acs.est.8b02791.

Södersten, C.J.H., Wood, R., Hertwich, E.G., 2018b. Endogenizing capital in MRIO models: the implications for consumption-based accounting. Environ. Sci. Technol. 52, 13250–13259. https://doi.org/10.1021/acs.est.8b02791.

Södersten, C.J.H., Lenzen, M., 2020. A supply-use approach to capital endogenization in input–output analysis. Econ. Syst. Res. 1–25. https://doi.org/10.1080/09535314.2020.1784852.

Sommer, M., Kratena, K., 2020. Consumption and production-based CO2 pricing policies: macroeconomic trade-offs and carbon leakage. Econ. Syst. Res. 5314. https://doi.org/10.1080/09535314.2019.1612736.

STATISTA, 2022a. Passange Cars - Europe.

STATISTA, 2022b. Population Projections in Italy.

STATISTA, 2022c. Projected Average Range of Electric Vehicles between 2020 and 2030.

STATISTA, 2022d. Annual Carbon Dioxide Emissions in Italy from 1970 to 2020.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 1979, 347. https://doi.org/10.1126/science.1259855.

Steubing, B., Koning, A De, Merciai, S., Tukker, A., 2022. How do carbon footprints from LCA and EEIOA databases compare? A comparison of ecoinvent and EXIOBASE. J. Ind. Ecol. 1–17. https://doi.org/10.1111/jiec.13271.

Suh, S., Weidema, B., Schmidt, J.H., Heijungs, R., 2010. Generalized make and use framework for allocation in life cycle assessment. J. Ind. Ecol. 14, 335–353. https://doi.org/10.1111/j.1530-9290.2010.00235.x.

Swiss Re Institute, 2020. Natural Catastrophes in Times of Economic Accumulation and Climate Change 2022. sigma 2.

Tao, F., Zuo, Y., Xu, L Da, Lv, L., Zhang, L., 2014. Internet of things and BOM-Based life cycle assessment of energy-saving and emission-reduction of products. IEEE Trans. Ind. Inf. 10, 1252–1261. https://doi.org/10.1109/TII.2014.2306771.

Tarei, P.K., Chand, P., Gupta, H., 2021. Barriers to the adoption of electric vehicles: evidence from India. J. Clean. Prod. 291. https://doi.org/10.1016/j.jclepro.2021.125847.

THE LOCAL se, 2022. Sweden to Set World's First Consumption-Based Emissions Target.

Tukker, A., Pollitt, H., Henkemans, M., Tukker, A., 2020. Consumption-based carbon accounting: sense and sensibility. Clim. Pol. 1–13. https://doi.org/10.1080/14693062.2020.1728208, 0.

United Nations, 2015. Adoption of the Paris Agreement.

van Capelleveen, G., Pohl, J., Fritsch, A., Schien, D., 2018. The Footprint of Things: a hybrid approach towards the collection. storage and distribution of life cycle inventory data 52. https://doi.org/10.29007/8pnj, 350–334.

Vita, G., Hertwich, E.G., Stadler, K., Wood, R., 2019a. Connecting global emissions to fundamental human needs and their satisfaction. Environ. Res. Lett. 14 https://doi.org/10.1088/1748-9326/aae6e0.

Vita, G., Lundström, J.R., Hertwich, E.G., Quistd, J., Ivanova, D., Stadler, K., et al., 2019b. Sustainable lifestyle scenarios to curb European environmental impact: connecting local visions to global consequences. Ecol. Econ. 164, 106322 https://doi.org/10.1016/j.ecolecon.2019.05.002.

Vita, G., Ivanova, D., Dumitru, A., García-mira, R., Carrus, G., Stadler, K., et al., 2020. Energy Research & Social Science Happier with less? Members of European environmental grassroots initiatives reconcile lower carbon footprints with higher life satisfaction and income increases. Energy Res. Social Sci. 60, 101329 https://doi.org/10.1016/j.erss.2019.101329.

von der Leyen, U., 2019. A Union that Strives for More: My Agenda for Europe, pp. 1–24.

West, T.A.P., Börner, J., Sills, E.O., Kontoleon, A., 2020. Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon 117, 24188–24194. https://doi.org/10.1073/pnas.2004334117/-/DCSupplemental.

White House, The, 2023. Building a Clean Energy Economy: a Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action.

World Bank Group. Carbon pricing dashboard. The World Bank 2022:1. https://carbonpricingdashboard.worldbank.org/map_data. (Accessed 4 August 2022).

Yaffe-Bellany, D., 2022. Crypto's Long-Awaited 'Merge' Reaches the Finish Line. New York Times.

Zhang, A., Zhong, R.Y., Farooque, M., Kang, K., Venkatesh, V.G., 2020. Blockchain-based life cycle assessment: an implementation framework and system architecture. Resour. Conserv. Recycl. 152, 104512 https://doi.org/10.1016/j.resconrec.2019.104512.

OECD. (2011). *Taxation, Innovation and the Environment: A Policy Brief* (Issue September). https://doi.org/10.1787/9789264087637-en.