energies

Perspective

A Carbon Accounting and Trading Platform for the UK Construction Industry

George Blumberg and Maurizio Sibilla *

School of the Built Environment, Oxford Brookes University, Abercrombe Building, Gipsy Lane, Oxford OX3 0DB, UK; gblumberg@brookes.ac.uk
* Correspondence: msibilla@brookes.ac.uk; Tel.: +44-(0)7747-638099

Abstract: Atmospheric carbon dioxide emanating from activities associated with the construction of buildings in the UK contributes approximately 16% of the UK's total emissions and will need to be reduced significantly to meet international agreements. Against this scenario, this paper presents a novel perspective for carbon accounting and trading that proposes the use of a platform for the UK construction industry as a possible solution. This suggestion assumes that taxation should be synchronised with phases of the entire life cycle of the building and that tax credits (or deficits) should remain an asset of the building itself. In this regard, a strategy is in place in the UK, but with gaps in how it will be implemented. To resolve these gaps, firstly, this paper explores and integrates three socio-technical components (i.e., carbon accounting, trading, and certification) that form an essential set of tools required for the management of taxes directed at property developers and construction companies. Then, it points out the need for a suite of computer-based systems to facilitate the recording of emissions information, the purchase of carbon offsets, and a way to access specialist financial services. As a result, a trading platform is conceptualised that makes use of blockchain technology as a foundation for future research.

Keywords: carbon accounting; carbon taxation; life-cycle analysis; blockchain; decentralized finance (DeFi)

Citation: Blumberg, G.; Sibilla, M. A Carbon Accounting and Trading Platform for the UK Construction Industry. *Energies* **2023**, *16*, 1566. https://doi.org/10.3390/en16041566

Academic Editor: Janusz Adamczyk

Received: 22 November 2022
Revised: 31 January 2023
Accepted: 2 February 2023
Published: 4 February 2023

1. Introduction

1.1. Convincing Evidence of an Accelerating Rate of Global Temperatures

There is convincing evidence of an accelerating rate of global temperature rise corresponding with an accumulation of carbon dioxide (CO_2) and other greenhouse gasses (GhGs) in the atmosphere [1]. In response to the threats associated with rising temperatures and other disruptions to the earth's atmospheric and oceanic systems, governments around the world, including the UK, have committed significant resources, planning, and laws. The main thrust of this action is that each country will reduce their emission of GhGs with nationally determined contributions (NDCs) as set out under the Paris Treaty ([2], Article 6) and subsequent agreements. If successful, this will lead to a reduction in emissions by at least 34% by 2020 and 100% by 2050, as compared with 1990 levels. The carbon dioxide equivalent (CO_2e) measure includes the relative contributions of the seven main Greenhouse Gases (weighted based on their impact on global warming) comprising: CO_2, methane (CH_4), nitrous oxide (N_2O) and hydro-fluorocarbons (HFC), perfluorocarbons (PFC), nitrogen trifluoride (NF_3), and sulphur hexafluoride (SF_6).

1.2. Rate Not Fast Enough to Meet International Obligations

However, the latest results from computer modelling, reported in IPCC [1] predict that the rate of global emission reductions will not be fast enough to achieve net zero by 2050. In the UK, this translates to a fall in emissions of 3.1%/yr. This is further confirmed, in a broader context, by a recent compendium of research on the mitigation of climate change published in IPCC [3], which concludes that the goal of a 1.5 °C limit in global average temperatures is unlikely to be achieved without significant action to reduce at source GhG emissions and for significant quantities of CO_2 to be extracted from the atmosphere and safely sequestrated in long-term storage. Carbon removal refers to directly extracting CO_2 from the atmosphere whereas carbon capture for use or storage (CCUS) involves industrial processes where CO_2 is captured from a smokestack or flue and then conditioned for re-use. For simplification, many researchers blur the distinction and refer to both processes as carbon capture. Both the current UK and US strategies require direct air capture (DAC) of CO_2 from the atmosphere, but neither fully specify how these will be implemented or financed.

1.3. Harmful to the Natural Environment

The IPCC reports have also pointed out that harmful processes, such as ocean acidification, rapid changes in land use, chemical and effluent pollution, stratospheric ozone depletion, atmospheric aerosol loading, and nitrogen and phosphorus use, are widespread and increasing. These also contribute to global warming by reducing the ability of the land to absorb CO_2 [4]. In the context of efforts to combat global climate change, the terrestrial and oceanic sinks of atmospheric GhGs are as important to restore and expand as the reduction in the sources of CO_2 [5]. This fact heightens the urgency of ongoing efforts. The mechanisms for emission reductions as well as the restoration of natural systems need to be revised to ensure that progress is made.

1.4. The Climate Change Act

Reassuringly, the commitment that the UK has made to reduce carbon emissions is enshrined into binding legislation with the Climate Change Act (henceforth, The Act) which empowers the government to enact regulations, initiate incentive programmes and raise taxes [6]. The Climate Change Committee (CCC), an independent statutory body is empowered under the Act to deliver these results. The CCCs industrial decarbonization strategy (see Ref. [7] for a review)) is further elaborated in the Sixth Carbon Budget, which includes sections specifically directed at the built environment [8]. The strategy addresses critical industries such as surface transport (representing 22% of 2019 emissions), manufacturing + construction + fuel supply (combined as 20% of the total), operation of buildings (17%), electricity generation (10%), agriculture (10%), aviation (7%), shipping (3%), waste disposal (6%), and from the escape of fluorinated gases (3%) and provides a roadmap for systematic reductions in emissions. The Act has, up to this point, been successful in helping to reduce GhG emissions in the UK [9] by 44% between 1990 and 2019 at a rate of approximately 1.4%/yr. Despite this apparent success, The Act, as it is currently expressed as regulation, will need significant reconfiguration and additional programmes if the UK intends to meet their international obligations [9]. This has led to speculation on how an additional tax or the imposition of a market mechanism, might be imposed.

1.5. Objectives of this Conceptual Study

The anticipation that some form of tax will be assessed on construction projects raises several questions that form the objectives of this study. These are: What is the likely course of action that the government will take to limit emissions in the construction industry? What future requirements for accounting and reporting for carbon emissions will be put in place? Will carbon be taxed on each project, or will companies be obligated to pay on an annual, operational basis? Will new services develop using blockchain technology, and what tools will be necessary for developers and builders to estimate emissions, submit accounts, pay taxes, transfer credits, receive refunds, and related functions? Is there any technology, either existing or under development, that could aid in this process?

2. Policy Considerations for Carbon Taxation

It is clear that substantive action will need to take place to achieve our legally-binding international commitments and that this will invariably involve significant economic costs. There is a growing movement for pricing carbon emissions as it allows for market mechanisms to alter the economic conditions to favour incremental reductions. There are policy implications associated with this [10].

Pricing CO_2 would provide a strong collective incentive for businesses, individuals, and families to consider emissions when making choices. It would also encourage innovation and adaptation in a move towards less consumptive behaviour. Furthermore, it is likely to change the way that buildings are procured, designed, financed, built, operated, refurbished, and dismantled. Amongst the policy consideration for building are: (i) Choice of emissions limiting mechanisms; (ii) Determination of an acceptable tax payment schedule for the full life cycle of buildings; (iii) Determine how different classes of buildings (hospitals, homes, infrastructure, schools, etc.) should be taxed; (iv) Choice of emission measurement methods for buildings; (v) Deciding on how to shift taxes to the end user; (vi) Determine the balance of tax, Cap and Trade, and other mechanisms; (vii) Ensuring that social justice is taken into consideration.

There is enough experience to judge the range of options that policymakers are facing and to consider the strong possibility that there will be a move towards taxing end-consumers.

2.1. Choice of Emissions Limiting Mechanisms and Measures

Burke et al. [11] and others have suggested that setting the price of carbon will be critical in achieving net-zero emissions in the UK and commented on the complexity of this task. If the price is too low, then polluters will have little incentive to invest in abatement or offsetting (i.e., paying others to extract and sequester carbon from the atmosphere). If the prices are too high, then the economy will be damaged and consumers exposed to high costs.

As first described analytically by Ref. [12], regulators could contain pollution by reaching a balance between permits to pollute (i.e., quantities determined by a Cap and Trade scheme) or by taxation (which sets a fixed price for CO_2 emissions). A uniform carbon tax on the construction and use of buildings has the advantage of providing certainty in cost, while a Cap and Trade scheme would provide certainty on the control of total quantities of carbon emitted on a project-by-project basis. A cap on the price of carbon would help achieve the legally binding obligation for emissions limitations by allowing the price of carbon to rise and fall based on supply and demand. This feature also allows those able to extract carbon from the atmosphere using natural or mechanical means to fund their activities.

Getting the balance right requires a highly complex policy strategy that would be a significant challenge for any government to meet. Although carbon taxes have the most obvious effects on consumers (in this case the renters and purchasers of building space), all carbon reduction policies will increase costs. This raises several issues, for example, social equality and justice. Price mechanisms for carbon emissions in the form of a tax can be regressive and disproportionally applied to certain segments of society. There is also the risk of double taxation, which should be avoided as it would impose added economic stress.

At present, no country uses a consolidated, uniform carbon tax code for all emissions across domestic and commercial polluters. The UK has, similar to other countries, a complex mixture of taxes, ETS and incentives that produce an uneven spread of costs for different classes of polluters that are levied at differing rates. Codes are not optimised for either tax revenue or economic growth. Adam et al. [13] has pointed out that carbon taxes, incentives, and other market mechanisms could play a crucial role in the incremental reduction in emissions, but that there should be an international effort to consolidate taxation around a standard and rational basis such as taxing the consumer or the end-user (preferably based on mass) rather than the producer.

During the extensive consultation process, criticism was received that embodied carbon is not receiving sufficient attention (see Ref. [14], for examples). This component of the carbon footprint, defined as the GhG emissions associated with the manufacturing of building components, materials, and processes, can make up a significant percentage of full life-cycle emissions as it includes carbon-intensive materials such as structural and reinforcing steels, cement, bricks, sheet, and finished timber products. Embodied carbon is calculated by adding up the CO_2 emissions required to manufacture, transport, assemble and commission materials and components used for construction. Emissions associated with disposal, once the components or structure are demolished, are also included. Embodied carbon may represent up to 50% of the total full life-cycle CO_2 footprint of a building and its demolition. For some, such as bridges, sports arenas, and other structures that have low operational carbon associated with them, the percentage of embodied carbon can approach 100% of the total. Müller et al. [15] summarised the role of infrastructure development in the context of moderating carbon emissions as it is closely connected with urban development, economic growth, health, and well-being. This lack of completeness in accounting for emissions is typical of most environmental laws.

Other than the UK Emissions Trading Scheme (UKETS) and the Carbon Price Support (CPS) programme, no other programme uses the mass of emitted CO_2e as a basis for taxation. Advani and Stoye [16] present a strong argument for end-consumer emission taxation based on the weight of CO_2e emitted, claiming that this would impact households directly and disproportionately to wealth. Policymakers could adjust taxation based on household income or some other measure.

Under current UK building regulations, design-stage calculated operational emissions (expressed in kgCO_2/m^2 per year) are submitted to a Building Control Body (BCB) along with an energy performance certificate (EPC). Approval is based on criteria established by the local planning office who then issue a certificate of occupancy. This approach has been effective in reducing emissions during the use of the building but provides no incentive for designers and builders to reduce embodied carbon.

Reforms are needed that would reduce the variation in carbon prices across different types of fuel. This approach has been criticised by Adam et al. [13] and others as missing a good opportunity to reformulate policy around a uniform and direct tax on harmful emissions.

Any tax or ETS imposed on the construction industry would require a significant reworking of existing regulations, notably Part L of the building code, which applies a broad set of environmental standards to all building and engineering work in England (Scotland and Wales have similar regulations that apply to buildings built in these countries).

2.2. A Tax Payment Schedule for the Full Life Cycle of Buildings

This section speculates that developers and builders will require a new set of tools to manage the imposition of a carbon tax on buildings. These are encapsulated in the conceptual model for a carbon accounting and trading platform (CATP). If there is, as predicted, a shift towards end-user carbon-based assessment, payments of carbon taxes will continue through the building's full life cycle. There are significant advantages to synchronizing the carbon accounting with milestones in the life-cycle of a building project, notably that governments will find it easier to tax developers by adding additional carbon taxes to existing fees and licenses rather than raising new taxes. For example, leverage could be exerted over builders by making payment for pollution a prerequisite for obtaining building consent, planning approval, occupancy permits, and, as the building reaches the end of its useful life, permission to demolish. The level of taxation could be variable or incrementally increased from year to year.

Figure 1 contains a timeline based on the RIBA Plan of Works and shows the milestones in the building life-cycle where CO_2e accounting, reporting, and trading take place. Financial services are required for the full life-cycle of buildings and the RIBA Plan of Work [17] provides a suitable framework.

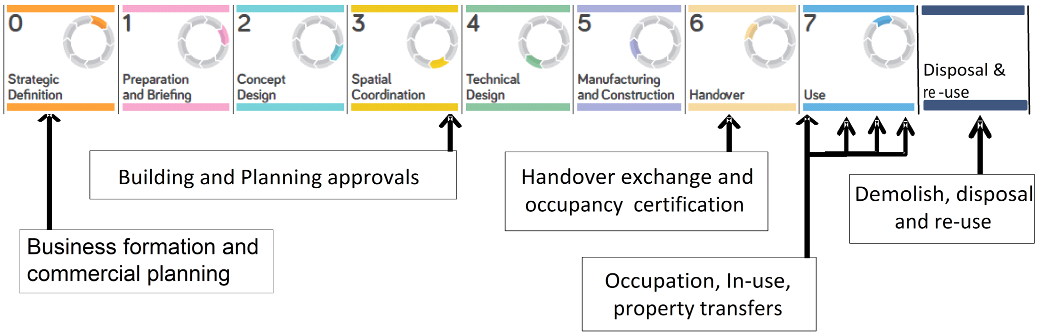

Figure 1. This diagram shows the phases of a typical building's life-cycle when CO_2e accounting, reporting, and trading are required. In this diagram, the RIBA Plan of Works serves as a base timeline (©G.M.C.Blumberg).

It is also likely that in the UK at least, taxes will be assessed and paid throughout the life cycle of the building. These start during the planning phases (when developers already pay fees) and continue while the building is in use, for example, when alterations are made and systems are upgraded. When the building is decommissioned and the materials are disposed of, a final assessment is made and taxes are paid. In the case of the Cap and Trade scheme for buildings, an assessment would require the purchasing of carbon tokens, equivalent to the mass of embodied and operational carbon up to the point they are paid. In this scenario, carbon credits would vest with the building itself and transfer as units of the building are bought and sold. In this way, carbon would be handled in an account that would operate based on credits and debits.

Raising new taxes is always a cause for concern as it would likely have economic and other implications. The government would have to be careful when applying them. The best approach would be to add them to existing taxes or fees and to fit the timing into legacy systems. One way to achieve this is to synchronize tax payments with building certifications, which occur at regular intervals as planning permission, building regulations completion certificate, energy performance certificate, ownership certificate, defects certificate, earthquake certificate, practical completion certificate and occupancy, established use certificate, and building demolition permission. Obtaining approvals represents a burdensome and bureaucratic aspect of construction in the UK and is considered one of the main impediments to higher profits in the industry.

2.3. Choice of Emission Measurement Methods for Buildings

A change in accounting towards measurements based on the mass of carbon emitted is crucial if the UK's CCC (as well as most other large-country climate change agencies) will continue with Cap and Trade schemes. There is strong momentum behind the use of market mechanisms to help reduce CO_2 emissions (see Ref. [13]).

Currently, most environmental laws do not use the mass of CO_2e as a basis for taxation. The UK policy for the building sector is mostly based on energy use as a proxy measure for CO_2e emissions. However, these vary widely depending on the user, type of energy, and fuel consumed. This creates inefficiency as it frequently leads to over or under-taxation or, in some cases, double taxation. The UK shares with other countries the resistance to additional taxes raised from households and many of the policies target the big polluters; however, this just pushes the problem of who pays for pollution upstream. This makes it impossible to estimate the amount of damage done by the polluter. For example, the Future Homes Standard (FHS), set to become law in 2025, targets a part of the construction industry by requiring that all new homes must be designed and constructed in such as way that they emit 75–80% less carbon than homes built under current regulations.

2.4. Ensuring That Social Justice Is Taken into Consideration

There is a strong moral argument for ensuring that whatever market mechanism is used, climate justice is led by climate economics; see the study by Sayegh [18]. This argument is based on the notion of a right to energy coupled with the duty of do-no-harm, which can be achieved by compensating those that are less able to pay. Everyone has the right to pollute as long as they can pay for the damage caused. If they cannot pay, then society should cover these costs.

Hepburn [19] and others pointed out that environmental success is based on governmental success and that leaving things solely to corporate social responsibility and altruistic consumer and shareholder preferences will not deliver the required results. On the other hand, leaving all notions of environmental protection in the hands of the government is likely to fail because government agencies rarely have the depth of expertise required to manage the complex tasks associated with environmental protection.

Unlike other taxes, such as value added (VAT), income tax, national insurance, and corporate tax, which are assessed on the end user, those raised to combat climate change (as described in the Sixth Carbon Budget) are applied to a limited group of big polluters, but without much reference to one of the basic tenants of environmental conservation: that the polluter pays [20].

In a recent review of existing environmental policy oriented towards buildings, Skillington et al. [21] concluded that as improvements in operational emissions for buildings have progressed, the relative importance of indirect or embodied energy has as well. As a result of this, policies addressing this portion of energy and emissions reductions are being proposed. In at least four countries—Australia, Canada, the USA, and the UK—voluntary actions are addressing this area. Regulatory measures for embodied carbon are largely absent at a national level. However, the private sector is showing an increase in the number of companies that regularly report their complete carbon footprint as a form of good environmental and social responsibility.

2.5. Reforms to Ensure Uniform Tax Rates and the Price of Carbon

Policymakers will also have to consider the potential uneven impact on certain segments of the population who may have lower resilience (and greater sensitivity) to price increases of basic commodities. This same sentiment is also one of the key issues in arriving at international agreements [22] where there is genuine concern that a carbon reduction policy could lead to even greater social inequality.

There are implications for the procurement of public buildings under more stringent environmental regulations. Pouikli [23] provides an analysis for EU public procurement, providing a useful example of the issues raised.

Considering that this is a moving-target problem of global complexity, and given the extent of uncertainties about almost every aspect of politics, science, and economics, policymakers will need to administer changes to CO_2 taxation with the same sensitivity that they approach income tax or value added tax (VAT). Policymakers have a limited number of options but must work alongside companies and individuals to improve the atmospheric carbon budget. It is assumed that the UKand other governments will revise their strategies to ensure that the agreed-upon targets can be achieved and to engage fully with theirs. This includes several measures, such as expanded use of market mechanisms such as direct taxation or an ETS [24].

There have been proposals from economists to create a new class of tax that takes into account the damage that a product or process would have on the emissions balance. Ref. [25] suggested replacing a value-added (VAT) or sales tax to damage and value-added tax (DaVAT) partially based on life cycle assessment (LCA) of materials and services. DaVAT would add a premium to all goods sold to consumers and, similar to VAT, the end consumer would bear the full cost of the tax with the main advantage of the removal of double taxation and creating a more uniform and transparent tax regime. The additional costs will force the reduction in the use of goods and services that seriously harm the environment and human health will be priced up, and those that impact them less will be priced down. The paper reflects on the proposal made by De Camillis and Goralczyk [26], where new market mechanisms (for example, Cap and Trade) are adopted for a full life cycle perspective. This is proposed in the form of a fiscal framework, based on VAT which has been chosen due to flexibility (i.e., by allowing different rates to be applied) and that these affect market prices as well as emissions. Using a hypothetical case study and a simulation experiment, the authors show that price mechanisms coupled with LCA can help to reduce emissions. These results confirm the work of Advani and Stoye [16], who demonstrate that non-uniformly distributed energy taxes are fraught with problems and have the opposite of their intended effect. For example, reforms that raise a direct tax on households would help improve the efficiency of emissions reduction efforts, although some adjustments would need to be made to support poor households.

2.6. Funding Carbon Capture and Sequestration

Although no universally agreed-upon system can reliably value the natural environment as a sink of CO_2 [27], there are methodologies that are followed by organizations such as Verra, who will quantify the capacity of a track of land to absorb and sequester CO_2. The latest plan is to fund carbon capture, usage, and storage (CCUS) from the central government through the newly established Infrastructure Fund (CIF) [28], which forms part of the government's Ten Point Plan for a Green Industrial Revolution, with commitments focused on driving technological innovation and simultaneously, a shift to renewable energy sources. These plans are relativity modest, with CCUS deployed in only two clusters in the UK by the mid-2020s, and four clusters by 2030. Once fully realised, these will capture 10 $MtCO_2$ per year. This quantity is not sufficiently large enough to meet the growing demand for carbon extraction. Indeed, Smith et al. [29], analysed the state of carbon dioxide removal worldwide and concluded that a large gap exists between the quantities of CO_2 that countries are planning to remove and the capacity of carbon removal systems.

2.7. Cap and Trade and a Carbon Marketplace

The most promising mechanism for providing funding for CCUS and natural ecosystem repair is to apply a modified Cap and Trade scheme [30,31] to control carbon emissions. Although it does not have the same certainty in terms of setting a fixed price for a ton of CO_2 extracted, it could ensure that emissions can be held in a constant quantity. The downside is that the price of carbon will follow the market demand and to some extent, we are relying on the invisible power of the marketplace to ensure our future. However, by creating an open market, suppliers (i.e., those able to extract CO_2) will have a marketplace through which they can sell, nominally in the form of a token that can be traded electronically.

Cap and Trade has been criticised for both a failure to enhance natural resources, such as forests, oceans, and peat bogs and for not doing enough to reduce emissions. Furthermore, Carl and Fedor [32], by tracking global carbon revenues in a worldwide survey, compared Cap and Trade with direct taxation. This revealed that 70% of Cap and Trade revenues (totalling USD 4.60 billion) is earmarked for green spending: roughly the same proportion of direct carbon tax (72% or USD 15.6 billion) is refunded to those paying or used for general government expenses.

Despite their shortcomings, Cap and Trade schemes are the most popular form of Emissions Trading Schemes (ETSs) and are in use or are planned to be used in over 60 countries [33,34]. According to data published by the World Bank, the 34 national jurisdictions that use Cap and Trade cover 11.65 Gt of CO_2e, a quantity that represents 21.5% of the total global emissions.

Modifications are required to adapt the existing Cap and Trade schemes to a more suitable configuration. At present, they require a central regulatory authority that allocates (or sells) licenses to discharge pollutants annually. The administration also sets the price cap, administers emission reports, manages payments, and ensures compliance. Payments into the scheme are in the hands of the central authority and there is no way to ensure that money will be directed to operators of CCUS or those restoring the environment.

ETSs and in particular Cap and Trade have attracted abundant criticism, with the main complaint being that under current configurations, the cap on emissions is not low enough to achieve the net-zero goals. Additionally, while they might work in reducing CO_2 emissions reasonably well for large, localized polluters such as steel plants and energy producers, they are not effective for fragmented industries such as manufacturing and construction, where the production of components can simply move to locations where there are little or no controls on pollution (the so-called leakage problem).

3. Changes to the Working Practice of Developers and Project Managers in Construction

A carbon tax on the construction of buildings and engineering structures will incur additional costs that will be borne by property developers, construction companies, and in particular the project managers. The risk profile will be altered by the inclusion of additional taxes and project success novel challenges will have to be overcome when dealing with the imposition of carbon taxes. Indeed, such changes could impact a very broad range of project priorities, such as financing a project and achieving sustainability goals, obtaining occupation, and the change of use or demolition certification. The threat to project viability would likely be a powerful driver in motivating construction companies and stakeholders to engage in a systematic and persistent reduction in both embodied and operational emissions. It is also expected that they would rely on tools and platforms that would assist them in managing these challenges.

This is likely to have an impact on the building process, including later stages when the building is in use and when it is eventually demolished and the materials are disposed of. Aspects that are specific to the construction industry are likely to be policy-related factors. These are: (i) They can be delineated from other industrial sectors because they are project-based and have a defined timeline; (ii) A building has a carbon footprint that remains relevant for the full life cycle and may vary from year to year; (iii) Developers, owners, and tenants make regular payments to government agencies, whether it be for certificates, council tax, surveys, and other government services. Crucially, these payments are associated with unique identification numbers; (iv) Estimates of the carbon footprint can be made at any time using modern software based on the application of standard models; (v) Costs associated with carbon offsetting and tax payments can be accounted for separately from other building-associated costs; (vi) Specialist financial services, oriented towards environmental compliance, can be accessed.

3.1. The Introduction of Carbon Accounting for Buildings

There is evidence that there is a shift by the Government towards a carbon-based taxation regime. Significantly, the CCC plan to assess whole-life carbon and material use of public and private construction projects is mandatory by 2025 and will require the implementation of a standard approach to reporting and accounting ([9], p 39). A bill has recently been introduced to Parliament by Jerome Mayhew, Conservative Member of Parliament for Broadland (see Ref. [35], for Jerome's reading of the bill). Thus a shift to carbon accounting for project-based construction work may become a legal requirement. One sign that the UK is moving towards a ETS for the construction industry is the expected requirement that reporting and standardized accounting will become obligatory [36]. Such a requirement can be seen as the first step in charging fees for CO_2 emissions during the life-cycle of a building, most likely to start as a payment when submitting a planning application.

3.2. Carbon Accounting and Reporting

In project-based accounting, the standard approach for estimates of the carbon footprint is to apply the GhG Protocol [37], as a formal method to identify, explain, and provide options for GhG inventory management. Under this protocol, estimates are made under ISO 14064, an international family of standards (see Ref. [38], for an overview) that comprises three parts, which detail the specifications and guidance for the organizational (ISO 14064-1:2006) and project levels (ISO 14064-2:2006), and validation and verification. They can be used independently or as an integrated set of tools to meet the varied needs of GhG accounting and verification (ISO 14064-3:2006). Included within the ISO 14064 standard is the facilitation of market mechanisms for reducing emissions.

The first stage in controlling carbon emissions from a construction project is to measure them. There are several approaches to measurement. For example, Kennelly et al. [39] propose a hybrid method for quantifying embodied and operational carbon emissions using life-cycle analysis (LCA). Ren and Li [40] published a review of carbon accounting models for the urban building sector, pointing out the need for a standardised approach. Others, such as Evans and Sidat [41], Cipriano et al. [42], focus on how to calculate CO_2 emissions in the built environment to implement new protocols for market mechanisms. Wang et al. [43] introduces the usability of an ecological service platform for carbon trading. Even though this work focuses on forest carbon reserves (rather than construction), it remains a useful indication of a quantitative approach. Wong et al. [44] explored the possibility that energy efficiency ratings and carbon accounting can affect the industry practitioners' decisions in building design and operations, pointing out that while stakeholders have a good understanding concerning energy efficiency, in general, misconception abounds on its relevance for the construction industry.

Meanwhile, Arnold et al. [45] have provided incentives for opening the debate on changing the building regulations by re-imagining the UK building codes by suggesting universal LCA for all projects.

3.3. Carbon Trading with Electronic Markets

Recently, Yan et al. [46] stressed how the development of digital technology brings with it the promise that it could provide opportunities to mitigate environmental problems. In detail, this study explored the state-of-the-art of digital transformation in the construction industry, focusing on analytical tools. Results indicated that the digitalization level of carbon-related topics is still at an early stage.

Some anticipate the growth of an international market that will provide an inclusive platform where quantities of carbon credits can be bought by those polluting and sold by those who can absorb and sequester equivalent quantities [47,48]. This financial feature is seen as being critical in creating a market mechanism that will effectively reduce the global levels of atmospheric CO_2. The trading price of CO_2 would be determined by the market forces of supply (availability of emissions units) and demand (level of offsetting requirements). The design, management, and policing of this marketplace would represent a significant step forward in efforts to combat global climate change as it would provide a financial incentive to improve the natural environment.

Fragments of a carbon market are in place in the UK, notably through the Woodland Carbon Code [49], which provides landowners with the ability to quantify their ability to successfully harness and sequester atmospheric CO_2 via land management and reforestation. The code provides an incentive to preserve or expand woodland through the issuance of carbon credits, which can be sold back to the government at a guaranteed price or used to compensate for UK-based greenhouse gas emissions. The Code works fine for small landholdings, but if expanded to encompass larger domains, then it would be a significant challenge to administer and police. It is clear that an international, inclusive, credible, and efficient market will take some time to evolve [47,48,50]. The establishment of a global market will likely proceed piecemeal. A suitable price on carbon emissions would be equivalent to the cost associated with carbon removal and sequestration. Success in carbon capture and sequestration will be, apart from technical and managerial innovations, dependent on the level of money available to fund these activities. For a carbon market to work efficiently, it needs to be regulated, policed, and supported by a clear set of rules and regulations. Under such a scenario, market forces will be the main driver to reduce carbon emissions. This, in turn, will be influenced by the price of traded carbon credits on open markets. The Report of the World

Bank's High-Level Commission on Carbon Prices [51] estimated that the appropriate carbon price across the world will need to be USD 40–80/tCO_2e by 2020, and USD 50–100/tCO_2e by 2030, to achieve sufficient levels of reduction.

3.4. Measuring Tools for Developers and Constructors

The main tool that a developer or constructor would use to obtain estimates of the embodied and operational carbon emissions is LCA performed repeatedly over the full life span of a building. In the construction industry, the most common tool is to make use of commercial LCAsoftware, which is capable of estimations of both embodied and operational CO_2e. Developers of the project will be required to purchase or sell carbon credits on the open market depending on whether their audits result in a net positive or net negative CO_2e contribution. Modern versions of database-centred LCA software such as One Click LCA www.oneclicklca.com/ (accessed on 3 February 2022) use advanced big-data techniques to constantly update materials and components in the supply chain, ensuring precise estimates of environmental product declaration (EPD) [52]. Individual components are included in the accounting by the use of environmental product declaration using the standard approach as described in CEN [53]. Users of this system would enter the location of the project to get the precise distance to the plant, production facility, or warehouse for accurate estimates of the embodied carbon.

4. Project Management and Carbon Reductions

Increasing direct taxation on carbon emissions for buildings will impose additional responsibilities on property developers and project managers by requiring them to engage in the monitoring, recording, and reporting of carbon emissions and the payment of taxes. Refs. [54,55] summarised the need to address the issues associated with sustainability and proposed a framework that includes elements of business strategy development, portfolio, and stakeholder management. Mavi and Standing [56] concluded that the inclusion of sustainability in project management raises the role to be central in ensuring critical success factors. Analysis points to leadership, sponsor support, stakeholder expectations, and end users imposed restrictions as the most important success factors. This section contains a discussion of these topics and is linked with suggestions for technical support in the conclusions of this work.

From the point of view of the project manager, as shown in Figure 2, the three components of the CATP are shown. These are illustrated as interlocking circles in the figure and provide facilities for (i) A trading platform for carbon emissions; (ii) A suite of financial services, and; (iii) A web-based certification and regulatory system.

This modular CATP is designed as a tool to help manage aspects of the project associated with accounting, recording, offsetting, and paying for and financing carbon emissions.

Contained in the platform are links to financial service organizations that specialize in managing carbon offsetting. These include (but are not limited to) loans, hedging against currency exchange exposure, insurance, current and savings accounts, and so forth. The lower-most circle in Figure 2 contains items associated with certification and licensing. These include planning permission, building control, environmental rating certification as well as machinery warranties, and professional service guarantees.

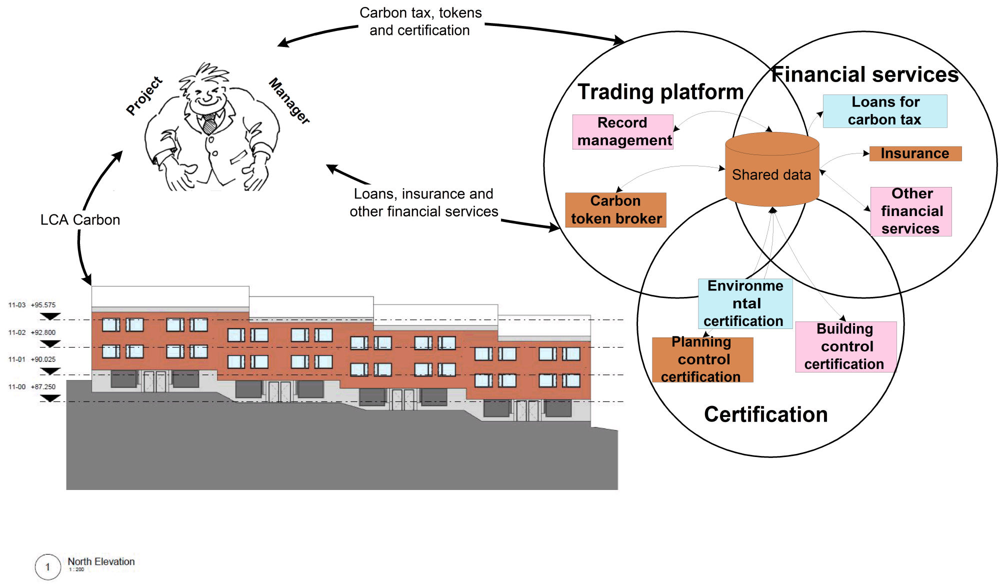

Figure 2. This schematic shows a manager of a building project with access to a CATP (©G.M.C.Blumberg).

4.1. Financing Full Life-Cycle Carbon Taxation

It is expected that carbon taxation will be done iteratively as it corresponds with the nature of the progress of a building from design, through to construction, and then into use. Under the scenario envisioned here, an up-front tax on CO_2 emissions is made to obtain planning permission. The amount paid is based on estimates made with outline drawings, but before any procurement starts. It is only possible to estimate the mass of carbon contained in the embodied components, materials, and the operational carbon emissions associated with transport and other energy-consumptive construction processes. This uncertainty can be accommodated within the payment regime and is illustrated in Figure 3, which contains a timeline that shows how the accuracy of emitted mass improves as the project progresses. The timings of the payment are synchronized to the RIBA Plan of Works and if overpaid at one point, credits can be saved in the owner's account and either sold or used for the next payment.

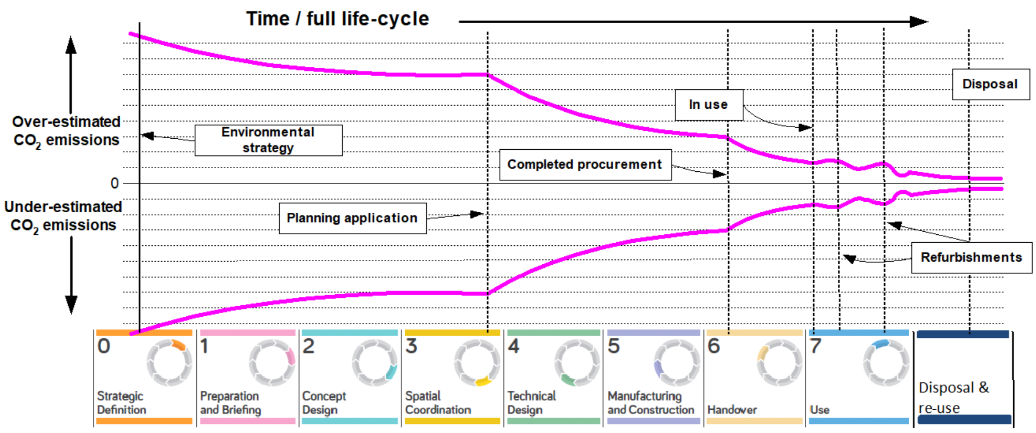

Figure 3. This graph shows the estimating trumpet that is adapted from Estimating Accuracy Trumpet, by R. Max Wideman (accessed on 27 May 2022 from http://www.maxwideman.com/). The graph illustrates how the accuracy of carbon emissions, both embodied and operational, becomes more precise as the life cycle of the building advances.

One significant advantage of this is that the costs associated with carbon offsetting can be separated from the normal building budget and treated differently. As there is already a growing number of specialist environmental funds that are becoming available, a specialist financial service sector can provide much-needed services to building developers and owners.

Most of the groundwork for this long-term carbon budget can be formulated during the pre-construction phases when the business case and elemental design for the building are being developed, and estimates can be based on the build based on its intended use, the number of floors, gross floor area, and frame type. Modern versions of software make use of a database, which is continuously added to and updated. It is at this point that design changes, procurement, and fabrication decisions can be made that would minimise the overall full life cycle carbon costs for the building.

Developers, builders, and occupiers that are obligated to provide life-cycle carbon offsetting for buildings would benefit greatly from access to a suite of financial services. These are listed and summarized in Table 1. This table includes the type of service, its use, and RIBA stages where they are needed. Whatever the case, the shift to carbon-reporting and taxing an industrial base is likely to concentrate a large amount of money that will require financial considerations relative to their importance and geographical distribution. This system must uniquely be global as the environmental crisis has no borders. Ideally, there should not be, for example, any one country or entity that dominates the trade.

Table 1. A list of financial services useful for developers and constructors to manage their carbon budgets and minimize full life cycle carbon emissions.

Financial Service	RIBA Stage	Action
Borrowing	Stages 0, 3, 6, and 8	Borrowing is essential for distributing up-front costs for CO_2e offsets over the entire life-cycle of the project. A specialist market in lending can be expected to grow.
Lending	Stages 0–8	In the DeFi ecosystem, extra capital from the building owners can provide much-needed liquidity for those who require money for CO_2e offsetting.
Insurance	Stages 0, 3, 6, and 8	Insurance is required for developers and builders to manage risks associated with unexpected events in CO_2 offsetting (e.g., safeguarding against underpayment or fines for non-compliance to regulations).
Stable CO_2 coin	Stages 0–8	A stable coin is a form of cryptocurrency that is closely tied to a stable fiat currency. An algorithm would ensure that there is relative stability in the price of CO_2e tokens.
Derivatives	Stage 0	These provide a useful service for hedging against rapid price fluctuations in CO_2e prices during the long life-cycle. This would be similar to the use of an insurance policy.
Carbon token marketplace	Stages 0, 3, 5, and 8	Would provide a managed and regulated exchange that would allow the buying (for emitters) and selling (for those who can capture and sequester) of CO_2e tokens.

Financial tools, such as loans and insurance, would pay for the large sums of money required to fully offset CO_2 emissions. Since the carbon credits purchased at the start of a project will remain associated with a building, then the investment would transfer to any new owner, part owner, or leaseholder. The financial structure of the project would therefore include any CO_2 tax paid, insurance for failure in design or operational standards, and derivatives to help hedge against currency (or token) exchange rate fluctuations. These mechanisms will help to optimize the CapEx and will if the policy is appropriate, minimize OpEx, the long-term operating costs (see [57], for an example of a study in this rich area of research).

Under any taxation regime that requires payment of a carbon tax as part of the building process, carbon tax payments are included in the project budget and therefore fall within the realm of the developer and project manager. In this context, the developer is required to balance the capital expenditures (CapEx), which includes the cost to assemble the structure, foundation and flooring systems, insulation, and cladding, mechanical, and electrical (M&E) services. Regular operating expenses (OpEx) incurred during the day-to-day activities of the occupiers, can be significantly altered by thoughtful designs introduced during the pre-construction phases. These are indicated by the leftmost arrow in the RIBA PoW shown in Figure 1; business and operational decisions are made that have long-term impacts on the environmental sustainability of the building. Developers with a long-term vision about the quality of the building, notably institutional owners (often with showcase architects), are more likely to opt for a larger initial budget (i.e., CapEx) that might contain superior materials, fine architectural detail, as well as a higher quality building envelope and improved M AND E systems. Part of the motivation for this higher expenditure would be to limit OpEx by reducing the energy demands. On the other hand, some developers, with a shorter-term commercial horizon, would pay less attention to OpEx savings and opt to minimize CapEx. These upfront cost-savings might boost short-term profits and appear commercially attractive for investors, but at the expense of longer-term savings, particularly if there is a carbon tax to pay.

Despite the uncertainness associated with emissions estimates before detailed designs are complete, it is, for several reasons, an ideal point for the government to impose a tax. As a starter, official certification requires the developer to pay a fee. In the UK, for example, these can be significant and can increase the overall cost of the building by several percentage points. In the UK, a planning application is submitted during the RIBA Stage 3 phase and marks the start of the project from an administrative point of view. At this point, the architects will have produced a Design and Access Statement, a requirement for buildings larger than 1000 m^2 and/or housing projects with more than 10 dwellings. This statement would not normally contain enough detail for contracting and constructing purposes (which would be elaborated in Stage 4, The Technical Design) but would contain sufficient information to make a preliminary estimate of the embodied and operational carbon emissions calculated for the full life-cycle of the building.

The handover is a critical phase (RIBA 6) in the building cycle and the UK as the control of the building passes to the occupier, and the management, as well those occupying the building, change. This is also the point where most of the embodied CO_2 is sealed up in the building fabric, fixtures, fittings, and systems. Accounting needs to be done during this time to reconcile the carbon that was embodied in the structure and systems. At this point, the developers will have amassed enough carbon credits to cover the components, material, and energy used during construction and a final reconciliation allows the developer to sell back excess credits into the marketplace or retire (in effect, destroy) credits that represent the CO_2 embodied in the building. The developer will be incentivized to minimize the CO_2 footprint by the high cost of buying CO_2 credits and will be able to benefit from changes to the design, construction, or process that have led to a smaller CO_2 footprint. With occupants in the building, heating, ventilation, and cooling can be commissioned. This marks the turning point when operational carbon starts to dominate the emissions. It is at this turning point that tax regimes, as well as ownership, are likely to change. This has implications for the design of the CATP which are summarised in this section.

4.2. Decentralized Finance for Carbon Accounting, Trading, and Services

Decentralized Finance (DeFi) is the term given to a collection of web-based algorithms that use smart contracts embedded in blockchains to provide financial services. The history of DeFi can be traced to the introduction of BitCoin by Nakamoto [58]. Although not strictly speaking a DeFi system, BitCoin nonetheless spawned a series of competing cryptocurrencies and, most significantly, an ecosystem of financial services to cater to the huge sums of money that have flowed into this newly formed asset class. A new class of commercial organizations, called FinTech has grown up to capitalise on blockchains and other technology. The bulk of DeFi has grown up around the Ethereum blockchain. The main reason for this is that it supports smart contracts and has a relatively easy-to-use programming language called Solidity. Modern blockchain networks, for example, Cardano, Hyperledger Fabric, and Tezos can also host smart contracts, so it is not necessary to deploy a custom-made blockchain for use as a trading platform.

The use of an electronic, automatic, blockchain-enabled ETS has been suggested by Shu et al. [59], who benchmarked a proposed system against existing alternatives. This and other innovation suggests that DeFi may form a central role in the systematic lowering of concentrations of CO_2 in the atmosphere and the restoration of the natural environment. Perhaps not unsurprisingly, the private sector is leading way in creating systems and services for environmental purposes. In most cases, these are in response to voluntary actions connected to environmental social governance (ESG). For example, The Global Reporting Initiative [60] www.globalreporting.org (accessed on 21 November 2022) encourages companies to disclose environmental performance in the context of carrying capacities and for many, a well-formulated ESG programme is a prerequisite for obtaining investment. A good example of this is the BlackRock Group of companies, who have oriented their corporate as well as investment strategies around the path to net-zero CO_2 emissions. BlackRock and others have joined a widening group of companies [61] that have adopted the Science-Based Targets [62] an approach that provides guidelines and a set of protocols for the voluntary sector [63,64].

ESG has, in part, driven the use of blockchain technology for carbon abatement and environmental restoration, a set of projects and companies that are often referred to as Regenerative Finance (ReFi). This association with DeFi is the use of blockchains by harnessing their capability to automatically record transaction details [65] in complex trading environments that contain multiple layers of suppliers and providers who require a digital paper trail [66,67], using systems that are extendible and can be automated (see Ref. [68], for an overview).

Another advantage of blockchain technology is that transactions can be made independently of any central authority, a feature particularly useful in reconciling global climate issues when countries may not be entirely trusting of each other [69,70] and when payment delays introduce additional financial strain [71]. Indeed, further automation of a range of administration processes could provide a broad set of benefits [72,73].

The voluntary sectors appear willing to use novel technology. The companies and open-source projects that occupy this technological space are collectively striving to build an open, transparent, modular, and non-custodial financial services industry. This evolving commercial ecosystem is converging towards a fully functioning decentralized financial system that cannot be dominated by a single person or institution. The DeFi educational establishment, Finematics, hosts a series of educational videos and documents that can be accessed at https://finematics.com/history-of-defi-explained/ (accessed on 21 November 2022).

Some of the companies operating in the area of carbon accounting and trading are Toucan, a blockchain-enabled CO_2 trading platform used for voluntarily purchasing CO_2 credits in the form of digital tokens. Toucan works in conjunction with the CO_2 database, Verra, to verify, allocate, and then retire tokenized CO_2 sequestration assets. KlimaDAO, a cryptocurrency based on the Klima token, is backed by a real-world carbon assets. In a similar vein, Evolution Markets, acts as a broker (in essence, a controlled marketplace) for CO_2 offsets in global energy markets. Regen Network provides a platform to mint, retire, or transfer tokenized carbon credits. Moss.earth accepts cash payments that are converted into tokens and then uses the income to pay for the restoration of forests and other conservation actions.

5. Conclusion, Limitations, and Future Research

5.1. The Concept of a Carbon Accounting and Trading Platform

It is the organizations and projects listed in the previous section that make up the components of the CATP system as displayed in Figure 4. This includes systems for accounting and reporting, paying carbon taxes, financing these payments, and being able to claim credit when progress is made on reducing emissions beyond expectations. It is expected that the CATP would act as a single point of access for developers and building owners to access a collection of digital services associated with carbon accounting, reporting, certification, and taxation.

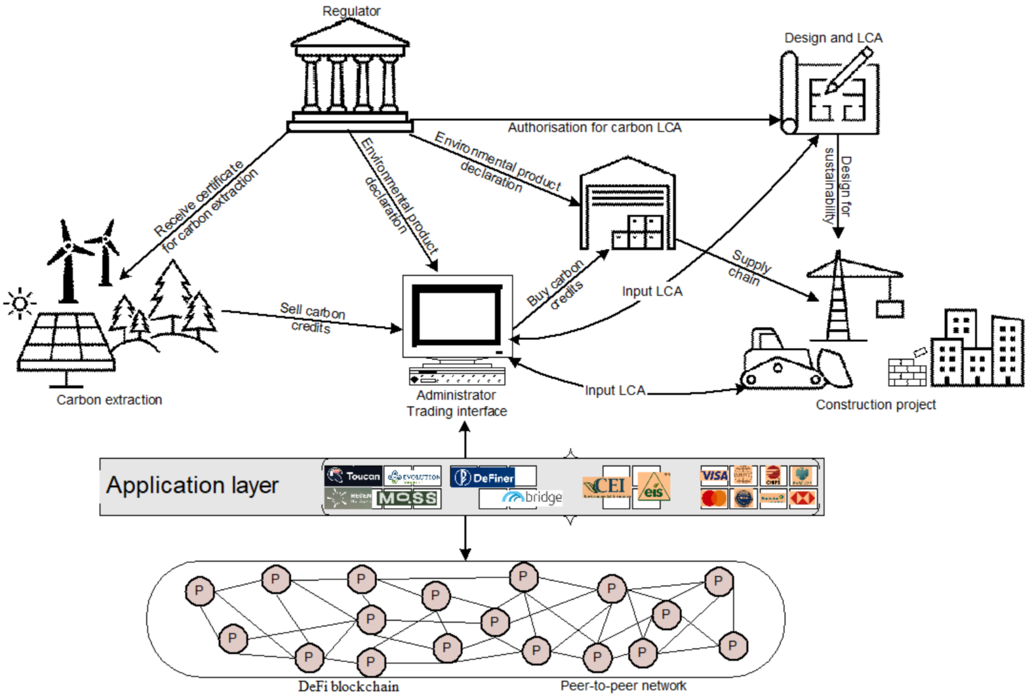

Figure 4. This diagram shows the trading network comprising the project administrator, government regulator, LCA analysis, supply chain network, financial, services, and blockchain technology (©G.M.C.Blumberg).

The upper portion of Figure 4 contains the schematic of a modified ETS that can provide funding for CO_2 capture and sequestration using an open trading platform. Six (6) elements are included in this portion (reading clockwise from the top): a regulator, a designer that issues regular LCAs, a storage facility representing the supply chain, a construction site, an administrator working through an API, and finally, an element that represents those capable of extracting and sequestering CO_2. In this system, the developer, at various points in the building's life-cycle, will perform a LCA and submit the results via the trading interface. Depending on the rates set by the regular, the developer is obligated to purchase a certain quantity of carbon offset credits. In this proposed system, these are purchasable as digital tokens on a blockchain-based online marketplace. The price paid by the developer for credits is dependent on the supply and demand and is automatically managed using algorithms and smart contracts. Suppliers delivering materials and components on site must provide accurate EPDs to the developer to include in their LCA estimates. At the same time, a collection of organizations and individuals that have issued carbon absorption tokens, sell these on the open market into a liquidity pool.

The lower portion of Figure 4 contains a schematic of the system that makes use of blockchain technology with smart contracts coupled with a relational database. The developer has access to blockchain-enabled trading systems as well as DeFi services tailored for use in environmental applications. For example, investors would buy into funds using an application-based cryptocurrency that would be added to a liquidity pool for the trading of carbon tokens. Investors would be rewarded with fees that are based on transaction fees, interest payments, and gains associated with the open-market price of the base cryptocurrency. Additionally included in Figure 4 is a collection of peers, who represent an essential element of all blockchain systems and who are identified by the symbol *P*. Carbon tokens, purchased by the developer, must be retired or erased so that they are not resold (which would result in a double entry error).

5.2. Conclusions

This paper integrated three socio-technical components (carbon accounting, trading, and certification) to prepare for new taxes to limit carbon dioxide emissions in the construction industry. The work provides a description of an essential set of tools. To arrive at this, the paper detailed some of the government's options for further limiting emissions in the construction industry and suggested that any future system would be based on market mechanisms. It should also include provision for financing CCUS and the restoration of natural carbon sinks, and be set up in a way that is economically efficient by avoiding double taxation.

The paper also suggested that taxation could be synchronized with phases of the full life cycle of the building and that tax credits (or deficits) should remain an asset of the building itself. Doing this would make it easier for consumers to accept the new taxes.

The use of LCA is proposed as the best way to estimate CO_2e for both embodied carbon in components and materials and emitted during use. LCA has the potential to provide a fair and balanced accounting basis that is sufficiently repeatable and scientifically based so that it can be used to assess taxes.

In synthesising the three components mentioned previously, a system is proposed that makes use of novel technology, notably the blockchain and the emerging DeFi industry. These have proven successful for regenerative finance in the private and voluntary sectors. A CATP, designed to serve the construction industry, could be assembled using nascent services, projects, and organizations.

The synthesis described here assumes that the UK government will expand the use of an ETS, modified from its present form so that it can be applied to the special dynamics of the UK construction industry as well as environmental goals. This envisions a new generation of tools that can manage high flows of information and money that will flow through the system.

This study was useful in identifying an important topic for the construction industry, which in turn defines the need for digital tools to integrate the carbon emission trading platform with financial services and regulatory systems. Secondly, the presentation of this conceptual model calls for the need to conduct additional empirical studies that could validate the efficacy and reliability of the proposed system. Multiple new avenues of research are opened and will be part of future work.

Author Contributions: Conceptualization, G.B.; methodology, G.B. and M.S.; validation, G.B. and M.S.; writing—original draft preparation, G.B.; writing—review and editing, M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approval were waived for this study as there were no human or animal participants used in the experiments or testing.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Nicholas Jelley of the University of Oxford who kindly reviewed the manuscript. The authors would also like to thank the staff and administrators of Oxford Brookes University for the material and other support provided for this research project.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modelling
CapEx	Capital Expenditure
CCC	UK Climate Change Committee
OpEx	Operational Expenditure
CCUS	Carbon capture, utilisation and storage
CATP	Carbon Accounting and Trading Platform
CO_2	Carbon Dioxide
CO_2e	Carbon dioxide equivalent
DeFi	Decentralized Finance
DApps	Decentralized applications
DLT	Digital ledger technology
EPD	Environmental product declaration
ESG	Environmental Social Governance
ETS	Emissions Trading Scheme
FinTech	Financial Technology company
FTSE	The Financial Times Stock Exchange Index
GhG	Greenhouse gases
HLF	Hyperledger Fabric blockchain
IBM	International Business Machines
ISO	International Organization for Standardization
IPCC	Intergovernmental Panel on Climate Change
LCA	Life-cycle analysis
M&E	Mechanical and electrical services
NDC	Nationally determined contribution
NBS	Nature-based solution
RIBA	Royal Institute of British Architects
UK	United Kingdom of Great Britain and Northern Ireland
DaVAT	Damage and valued added tax

References

1. IPCC. AR6 Climate Change 2021: The Physical Science Basis. In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/ (accessed on 21 November 2022).
2. United Nations Framework Convention on Climate Change. Paris agreement. In Proceedings of the Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change on Its 21st Session, Paris, France 30 November–13 December 2015; Volume 4, p. 2017. Available online: https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf (accessed on 3 February 2012).
3. IPCC. AR6 Climate Change 2022: Mitigation of Climate Change. In *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Skea, J., Shukla, P., Kılkış, Ş., Eds.; Cambridge University Press: Cambridge, UK, 2022. Available online: https://www.ipcc.ch/report/ar6/wg3/ (accessed on 3 February 2012).
4. Galloway, J.N.; Townsend, A.R.; Erisman, J.W.; Bekunda, M.; Cai, Z.; Freney, J.R.; Martinelli, L.A.; Seitzinger, S.P.; Sutton, M.A. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* **2008**, *320*, 889–892. [CrossRef] [PubMed]
5. Zakkour, P.D.; Heidug, W.; Howard, A.; Stuart Haszeldine, R.; Allen, M.R.; Hone, D. Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage. *Clim. Policy* **2021**, *21*, 63–77. [CrossRef]
6. Government of the United Kingdom. Climate Change Act 2008 (2050 Target Amendment) Order 2019, Technical Report, UK Public General Acts 2008 c. 27, UK Statutory Instruments 2019 No. 1056. 2008. Available online: https://www.legislation.gov.uk/ukpga/2008/27/contents (accessed on 21 November 2022).
7. Hammond, G.P. The UK industrial decarbonisation strategy revisited. *Proc. Inst. Civ.-Eng.-Energy* **2022**, *175*, 30–44. [CrossRef]
8. Climate Change Committee. Sixth Carbon Budget: Buildings. Technical Report, Summary of the Content for the Buildings Sector from the Sixth Carbon Budget Advice, Methodology and Policy Reports. 2020. Available online: https://www.theccc.org.uk/publicationtype/0-report/03-carbon-budget/ (accessed on 21 November 2022).
9. Climate Change Committee. Net Zero Strategy: Progress in Reducing Emissions: 2022 Report to UK Parliament. Technical Report, The Climate Change Committee of Her Majesties Government, 2022. Presented to Parliament Pursuant to Section 14 of

the Climate Change Act 2008. Available online: https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/ (accessed on 3 February 2012).

10. Volz, U.; Beirne, J.; Ambrosio Preudhomme, N.; Fenton, A.; Mazzacurati, E.; Renzhi, N.; Stampe, J. *Climate Change and Sovereign Risk*; Technical Report; SOAS Centre for Sustainable Finance at SOAS University of London: London, UK; The Asian Development Bank Institute: Tokyo, Japan; The World Wide Fund for Nature Singapore: Singapore; Four Twenty Seven: Berkeley, CA, USA, 2020. [CrossRef]
11. Burke, J.; Byrnes, R.; Fankhauser, S. *How to Price Carbon to Reach Net-Zero Emissions in the UK*; Policy Report; London School of Economics: London, UK, 2019.
12. Weitzman, M.L. Prices vs. quantities. *Rev. Econ. Stud.* **1974**, *41*, 477–491. [CrossRef]
13. Adam, S.; Delestre, I.; Levell, P.; Miller, H. Tax policies to reduce carbon emissions. *Fisc. Stud.* **2022**, *43*, 235–263. [CrossRef]
14. *The Future Buildings Standard: 2021 Consultation on Changes to Part L (Conservation of Fuel and Power) and Part F (Ventilation) of the Building Regulations for Non-Domestic Buildings and Dwellings; and Overheating in New Residential Buildings: Summary of Responses Received and Government Response*; Technical Report; Department of Levelling Up, Housing & Communities: London, UK, 2021. Available online: https://www.gov.uk/government/consultations/the-future-homes-standard-changes-to-part-l-and-part-f-of-the-building-regulations-for-new-dwellings (accessed on 21 November 2022).
15. Müller, D.B.; Liu, G.; Løvik, A.N.; Modaresi, R.; Pauliuk, S.; Steinhoff, F.S.; Brattebø, H. Carbon emissions of infrastructure development. *Environ. Sci. Technol.* **2013**, *47*, 11739–11746. [CrossRef]
16. Advani, A.; Stoye, G. Cheaper, greener and more efficient: Rationalising UK carbon prices. *Fisc. Stud.* **2017**, *38*, 269–299. [CrossRef]
17. RIBA. *RIBA Plan of Works Overview*; Technical Report; Royal Institute of British Architects: London, UK, 2020.
18. Sayegh, A.G. Pricing carbon for climate justice. *Ethics Policy Environ.* **2019**, *22*, 109–130. [CrossRef]
19. Hepburn, C. Environmental policy, government, and the market. *Oxf. Rev. Econ. Policy* **2010**, *26*, 117–136. [CrossRef]
20. Barthakur, A. Polluter pays principle as the key element to environmental law. *Int. J. Sci. Res. Publ. (IJSRP)* **2021**, *11*, 274–277. [CrossRef]
21. Skillington, K.; Crawford, R.H.; Warren-Myers, G.; Davidson, K. A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings. *Energy Policy* **2022**, *168*, 112920. [CrossRef]
22. Chancel, L.; Piketty, T. Carbon and Inequality: From Kyoto to Paris Trends in the Global Inequality of Carbon Emissions (1998–2013) & Prospects for an Equitable Adaptation Fund World Inequality Lab. Working Paper. Available online: https://shs.hal.science/halshs-02655266 (accessed on 21 November 2022).
23. Pouikli, K. Towards mandatory Green Public Procurement (GPP) requirements under the EU Green Deal: Reconsidering the role of public procurement as an environmental policy tool. In *Proceedings of the ERA Forum*; Springer: Berlin, Germany, 2021; Volume 21, pp. 699–721. [CrossRef]
24. HM Government, Department for Business, Energy & Industrial Strategy. Net Zero Strategy: Build Back Greener. Technical Report, Presented to Parliament Pursuant to Section 14 of the Climate Change Act 2008. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf (accessed on 3 February 2012).
25. Timmermans, B.; Achten, W. From value-added tax to a damage and value-added tax partially based on life cycle assessment: principles and feasibility. *Int. J. Life Cycle Assess.* **2018**, *23*, 2217–2247. [CrossRef]
26. De Camillis, C.; Goralczyk, M. Towards stronger measures for sustainable consumption and production policies: Proposal of a new fiscal framework based on a life cycle approach. *Int. J. Life Cycle Assess.* **2013**, *18*, 263–272. [CrossRef]
27. If the World Loves Forests, It Should Put a Price on their Carbon. *The Economist Magazine*, 4 November 2021; Updated 8 November 2021. Available online: https://www.economist.com/international/the-world-should-prove-its-love-for-forests-by-putting-carbon-prices-on-them/21806086 (accessed on 21 November 2022).
28. Department for Business, Energy & Industrial Strategy. Policy Paper: The Carbon Capture and Storage Infrastructure Fund: An Update on Its Design. 2022. Available online: https://www.gov.uk/government/publications/design-of-the-carbon-capture-and-storage-ccs-infrastructure-fund/the-carbon-capture-and-storage-infrastructure-fund-an-update-on-its-design-accessible-webpage (accessed on 21 November 2022).
29. Smith, S.M.; Geden, O.; Nemet, G.F.; Gidden, M.J.; Lamb, W.F.; Powis, C.; Bellamy, R.; Callaghan, M.W.; Cowie, A.; Cox, E.; et al. *The State of Carbon Dioxide Removal*, 1st ed.; Technical Report; 2023. Available online: https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/63c8876b8b92bf2549e83ed5/1674086272412/SoCDR-1st-edition.pdf (accessed on 21 November 2022).
30. Leung, D.Y.; Caramanna, G.; Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technologies. *Renew. Sustain. Energy Rev.* **2014**, *39*, 426–443. [CrossRef]
31. Özler, Ş.İ.; Obach, B.K. Capitalism, state economic policy and ecological footprint: an international comparative analysis. *Glob. Environ. Politics* **2009**, *9*, 79–108. [CrossRef]
32. Carl, J.; Fedor, D. Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world. *Energy Policy* **2016**, *96*, 50–77. [CrossRef]
33. Lai, O. What Countries Have A Carbon Tax? Earth Org. 2021. Available online: https://earth.org/what-countries-have-a-carbon-tax/ (accessed on 3 February 2023).
34. Pearce, D. An intellectual history of environmental economics. *Annu. Rev. Energy Environ.* **2002**, *27*, 57–81. [CrossRef]

35. Mayhew, J. Presentation of Carbon Emissions Buildings Bill to the House of Commons. Video of 1st Reading in Parilament. 25 November 2022. Available online: https://www.jeromemayhew.org.uk/news/presentation-my-carbon-emissions-buildings-bill-house-commons (accessed on 6 January 2023).
36. House of Commons Environmental Audit Committee. Building to Net Zero: Costing Carbon in Construction. First Report of Session 2022–23. Together with Formal Minutes Relating to the Report, Ordered by the House of Commons. To be Printed 11 May 2022. Available online: https://publications.parliament.uk/pa/cm5803/cmselect/cmenvaud/103/report.html (accessed on 6 January 2023).
37. Greenhalgh, S.; Broekhoff, D.; Daviet, F.; Ranganathan, J.; Acharya, M.; Corbier, L.; Oren, K.; Sundin, H. The Greenhouse Gas Protocol for Project Accounting. Technical Report, The World Resource Institute and the World Business Council for Sustainable Development. 2004. Available online: https://www.wri.org/initiatives/greenhouse-gas-protocol (accessed on 3 January 2023).
38. Weng, C.K.; Boehmer, K. Launching of ISO 14064 for greenhouse gas accounting and verification. *ISO Manag. Syst.* **2006**, *15*, 14–16.
39. Kennelly, C.; Berners-Lee, M.; Hewitt, C. Hybrid life-cycle assessment for robust, best-practice carbon accounting. *J. Clean. Prod.* **2019**, *208*, 35–43. [CrossRef]
40. Ren, Z.; Li, X. A Review of Carbon Accounting Models for Urban Building Sector. In *Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning*; Springer: Berlin, Germany, 2014; pp. 617–624. ._68. [CrossRef]
41. Evans, B.; Sidat, S. The use of temporal factors for improved CO_2 emissions accounting in buildings. *Build. Serv. Eng. Res. Technol.* **2018**, *39*, 196–210. [CrossRef]
42. Cipriano, X.; Gamboa, G.; Danov, S.; Mor, G.; Cipriano, J. Developing indicators to improve energy action plans in municipalities: An accounting framework based on the fund-flow model. *Sustain. Cities Soc.* **2017**, *32*, 263–276. [CrossRef]
43. Wang, W.; Hoang, D.T.; Xiong, Z.; Niyato, D.; Wang, P.; Hu, P.; Wen, Y. A survey on consensus mechanisms and mining management in blockchain networks. *arXiv* **2018**, arXiv:1805.02707. https://doi.org/10.1109/ACCESS.2019.2896108.
44. Wong, P.S.; Lindsay, A.; Crameri, L.; Holdsworth, S. Can energy efficiency rating and carbon accounting foster greener building design decision? An empirical study. *Build. Environ.* **2015**, *87*, 255–264. [CrossRef]
45. Arnold, W.; den Dekker, T.; J., G.; Godefroy, J.; Sturgis, S. A Proposed Amendment to the Building Regulations 2010: Whole Life Carbon (Part Z). 2021. Available online: https://part-z.uk/ (accessed on 21 November 2022).
46. Yan, J.; Lu, Q.; Tang, J.; Chen, L.; Hong, J.; Broyd, T. Digital Tools for Revealing and Reducing Carbon Footprint in Infrastructure, Building, and City Scopes. *Buildings* **2022**, *12*, 1097. [CrossRef]
47. Prices in the World's Biggest Carbon Market Are Soaring. *The Economist Magazine*, 24 February 2021; Updated 28 February 2021. Available online: https://www.economist.com/finance-and-economics/2021/02/24/prices-in-the-worlds-biggest-carbon-market-are-soaring (accessed on 21 November 2022).
48. Can carbon markets reduce carbon emissions? *The Economist Magazine*, 1 October 2021. Available online: https://www.economist.com/films/2021/10/01/can-carbon-markets-reduce-carbon-emissions (accessed on 21 November 2022).
49. Jenkins, T.; Mackie, E.D.; Matthews, R.W.; Miller, G.; Randle, T.J.; White, M.E. FC Woodland Carbon Code: Carbon Assessment Protocol (v2.2), Forestry Commission Version. 2018. Available online: www.woodlandcarboncode.org.uk/images/PDFs/WCC_CarbonAssessmentProtocol_V2.0_March2018.pdf (accessed on 21 November 2022).
50. Carbon Markets Are Going Global. But Will They Make a Difference? *The Economist Magazine*, 26 May 2022. Available online: https://www.economist.com/finance-and-economics/2022/05/26/carbon-markets-are-going-global (accessed on 21 November 2022).
51. Stiglitz, J.E.; Stern, N.; Duan, M.; Edenhofer, O.; Giraud, G.; Heal, G.M.; La Rovere, E.L.; Morris, A.; Moyer, E.; Pangestu, M.; et al. *Report of the High-Level Commission on Carbon Prices*; Technical Report; International Bank for Reconstruction and Development and International Development Association/ The World Bank: Washington, DC, USA, 2017. [CrossRef]
52. Anderson, J.; Moncaster, A. Embodied carbon, embodied energy and renewable energy: a review of Environmental Product Declarations. *Proc. Inst. Civ.-Eng.-Struct. Build.* **2021**, 1–33. [CrossRef]
53. *EN 15804:2012+A2:2019*; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. European Committee for Standardization (CEN): Brussels, Belgium, 2019.
54. Pham, H.; Kim, S.Y. The effects of sustainable practices and managers' leadership competences on sustainability performance of construction firms. *Sustain. Prod. Consum.* **2019**, *20*, 1–14. [CrossRef]
55. Sánchez, M.A. Integrating sustainability issues into project management. *J. Clean. Prod.* **2015**, *96*, 319–330. [CrossRef]
56. Mavi, R.K.; Standing, C. Critical success factors of sustainable project management in construction: A fuzzy DEMATEL-ANP approach. *J. Clean. Prod.* **2018**, *194*, 751–765. [CrossRef]
57. Garcia, D.J.; You, F. Multiobjective optimization of product and process networks: General modeling framework, efficient global optimization algorithm, and case studies on bioconversion. *Aiche J.* **2015**, *61*, 530–554. [CrossRef]
58. Nakamoto, S. Bitcoin: A peer-to-Peer Electronic Cash System. 2008. Available online: https://bitcoin.org/bitcoin.pdf (accessed on 3 February 2023).
59. Shu, Z.; Liu, W.; Fu, B.; Li, Z.; He, M. Blockchain-enhanced trading systems for construction industry to control carbon emissions. *Clean Technol. Environ. Policy* **2022**, 1–20. [CrossRef]
60. Levy, D.L.; Szejnwald Brown, H.; De Jong, M. The contested politics of corporate governance: The case of the global reporting initiative. *Bus. Soc.* **2010**, *49*, 88–115. [CrossRef]

61. Bjørn, A.; Tilsted, J.P.; Addas, A.; Lloyd, S.M. Can science-based targets make the private sector Paris-aligned? A review of the emerging evidence. *Curr. Clim. Change Rep.* **2022**, 1–17. [CrossRef] [PubMed]
62. United Nations Global Compact, World Resources Institute (WRI); The World Wide Fund for Nature (WWF). Science-Based Net-Zero Scaling Urgent Corporate Climate Action Worldwide Science Based Targets Initiative Annual Progress Report, 2021. Version 1.2—Updated June 2022. Available online: https://sciencebasedtargets.org/resources/files/SBTiProgressReport2021.pdf (accessed on 21 November 2022).
63. Walenta, J. Climate risk assessments and science-based targets: A review of emerging private sector climate action tools. *Wiley Interdiscip. Rev. Clim. Change* **2020**, *11*, e628. [CrossRef]
64. Bjørn, A.; Bey, N.; Georg, S.; Røpke, I.; Hauschild, M.Z. Is Earth recognized as a finite system in corporate responsibility reporting? *J. Clean. Prod.* **2017**, *163*, 106–117. [CrossRef]
65. Chapron, G. The environment needs cryptogovernance. *Nature* **2017**, *545*, 403. [CrossRef]
66. Hultgren, M.; Pajala, F. Blockchain Technology in Construction Industry: Transparency and Traceability in Supply Chain. Master's Thesis, Royal Swedish Institute of Technology, Stockholm, Sweden, 2018. Available online: https://www.diva-portal.org/smash/record.jsf?dswid=-9416&pid=diva2%3A1229861 (accessed on 21 November 2022).
67. Penzes, B. Blockchain Technology in the Construction Industry. Technical Report, Institution of Civil Engineers. 2018. Available online: www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/News/Blog/Blockchain-technology-in-Construction-2018-12-17.pdf (accessed on 15 May 2022).
68. Wang, S.; Yuan, Y.; Wang, X.; Li, J.; Qin, R.; Wang, F.Y. An overview of smart contract: Architecture, applications, and future trends. In Proceedings of the 2018 IEEE Intelligent Vehicles Symposium (IV), Suzhou, China, 26–30 June 2018; pp. 108–113.
69. Tapscott, D.; Tapscott, A. How blockchain will change organizations. *MIT Sloan Manag. Rev.* **2017**, *58*, 10. Available online: https://www.proquest.com/scholarly-journals/how-blockchain-will-change-organizations/docview/1875399260/se-2?accountid=13042 (accessed on 21 November 2022).
70. Carroll, J.M.; Bellotti, V. Creating Value Together: The Emerging Design Space of Peer-to-Peer Currency and Exchange. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing, Vancouver, BC, Canada, 14–18 March 2015*; ACM: New York, NY, USA, 2015; pp. 1500–1510. [CrossRef]
71. Das, M.; Luo, H.; Cheng, J.C. Securing interim payments in construction projects through a blockchain-based framework. *Autom. Constr.* **2020**, *118*, 103211. [CrossRef]
72. Heiskanen, A. The technology of trust: How the Internet of Things and blockchain could usher in a new era of construction productivity. *Constr. Res. Innov.* **2017**, *8*, 66–70. [CrossRef]
73. Barbosa, F.; Woetzel, J.; Mischke, J.; Ribeirinho, M.J.; Sridhar, M.; Parsons, M.; Bertram, N.; Brown, S. Reinventing Construction through a Productivity Revolution. Technical Report, McKinsey Global Institute. 2017. Available online: https://www.mckinsey.com/business-functions/operations/our-insights/reinventing-construction-through-a-productivity-revolution (accessed on 21 November 2022).