The Social Value of Offsets

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ABSTRACT

How much carbon should be stored in temporary and risky offsets to compensate 1 ton of CO2 emissions? Measured in terms of economic damages avoided, we cast the Social Value of an Offset (SVO) as a well-defined fraction of the Social Cost of Carbon (SCC) reflecting offset duration, and risks of non-additionality and failure. The SVO reflects the value of temporary storage, and overcomes shortcomings in the climate science and economics of previous contributions.[1–4] The SVO is policy relevant. An efficient net-zero policy will consist of offsets if their SVO-to-cost ratio exceeds the benefit-cost ratio of alternatives. The SVO yields an indicator of the equivalence of offsets to permanent carbon storage measured by the SVO-SCC ratio. We provide a matrix of equivalence factors for different risks, permanence and climate scenarios. Estimation yields a rule of thumb: one offset sequestering one ton for 50 years is equivalent to between 0.3 to 0.5 tons permanently locked away. Equivalence offers a means of replacing perpetual offset contracts by simpler, easy to monitor short-term contracts, has applications to carbon Life-Cycle Analysis[5] and the valuation of carbon debts[6], and can be the basis of comparing offsets of different qualities in the voluntary and compliance markets.
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Introduction

To meet the target of the Paris Agreement and limit climate warming to well below 2C, 136 governments and 750 of the 2000 largest traded companies have made commitments to a net-zero programme for carbon emissions (zerotracker.net). Meeting these targets will require concerted action in the global economy and offsets, including nature-based solutions (NBS), are likely to be part of any Paris-compliant net-zero strategy[7]. Furthermore, any delay in meeting net-zero targets will lead to overshoot and emissions that will have to be offset in the future, so-called ‘carbon debt’[6].

Unfortunately, there are considerable uncertainties associated with offsets due to the unregulated nature of the global offsets market, and the difficulties of establishing successful projects. NBS in tropical forests are seen as particularly risky due to the absence of strong institutions on the ground to monitor, enforce and account for emissions sequestered[8]. Fires, either naturally occurring or due to concerted land-use change, and disease outbreaks are typical risk factors[9]. Perhaps more pervasive is the risk of non-additionality of credited projects: either they would have happened anyway, activity is displaced or there is double counting[10]. For instance, reported emissions reductions from REDD+ projects are either vastly overstated[11], partial[12] or minimal in relation to Nationally Defined Contributions (NDCs)[8]. Indeed, any offsetting technology can be subject to risk of impermanent implementation, failure or non-additionality[10]. These uncertainties lead to doubts about the comparability and fungibility of offsets and their ability to contribute to net-zero. In response, international initiatives, such as the Integrity Council for the Voluntary Carbon Markets (ICVCM), are attempting to find a common standard of integrity. So far, however, a metric of the social value of offsets is missing.

At the core of the offset fungibility issue is a valuation question: how many risky or temporary offsets are equivalent to a permanent removal of emissions? Our analysis shows that a carbon emission today which is offset by a temporary project can be thought of as a postponed emission with the same warming effect when the project ends, but with less warming during the project. The Social Value of Offsets (SVO) stems from the value of delaying emissions and damages, and this depends on how impermanent, risky or additional they are. Valuing offsets using the SVO then provides a means of comparing offsets with different qualities in terms of the welfare they provide.

Our approach harmonizes previous work, which has approached the problem either from a purely ‘physical’ perspective or a purely ‘economic’ perspective, and so lacked a complete treatment of both. Our approach includes a wider set of feedbacks in the ’physical’ perspective, links the analysis to economic damages and welfare, and shows that the SVO is always positive.

The physical strand of literature has focussed on the changes in the Global Warming Potential (GWP) of a project, i.e. the total extra energy absorbed by the earth over 100 years[13,14]. Our approach considers infinite horizons and focuses on the temperature effect, which is the relevant driver of economic damages. By using the FAIR model[15,16] the focus on temperatures accounts for thermal inertia and saturation of carbon sinks in addition to the carbon absorption cycle and decreasing marginal forcing considered in previous work. Furthermore, the physical literature only implicitly measures damages, typically with constant marginal damages that are independent of background warming. Our approach uses marginal damages that increase in temperature.

The economic strand of studies focuses on the economic value to society of emissions via a carbon price that reflects the cost of abatement[3,4]. Nevertheless, none specify a climate module, so they are limited on the physical side. More importantly, the focus on abatement costs and the absence of a marginal damage trajectory means that the carbon prices do not properly reflect welfare over time and have arbitrary trajectories: either constant over time or increasing at the rate of discount. However, the benefits of impermanent offsets/temporary storage stem from delaying damages, so it is important to use carbon prices that reflect the trajectory of damages when thinking about the welfare benefits of delayed emissions.

The SVO approach elaborated here harmonizes and updates these two strands of the literature by accounting for the most recent climate and economic science. The SVO is embedded in a Cost-Benefit framework where the SCC is the relevant carbon price and its trajectory over time is grounded in the climate science and economics. The SVO approach shows that temporary storage is over-valued if the carbon price is constant over time and under-valued if the carbon price increases at the discount rate. The former trajectory reflects an unusual set of climate-economy assumptions, while the latter arises where the valuation framework stems from Cost-Effectiveness Analysis (CEA). In the CEA framework the carbon price is based on minimising the abatement costs associated with a temperature constraint, (e.g. staying below 1.5C), rather than maximising welfare. With damages only implicitly included via the temperature constraint, the CEA valuation framework is insensitive to the timing of these damages before the temperature constraint is binding. By contrast, the Cost-Benefit framework includes damages explicitly and therefore allows delayed damages to be explicitly valued. The SVO extends previous economic approaches and allows us to conclude that CEA, while meaningful for climate policy in general, is misleading for valuing temporary offsets. Even when a Cost-Benefit approach is undertaken subject to a temperature constraint, our SVO formula remains applicable.

The SVO approach also has an explicit treatment of physical and economic risk, both at the project and macroeconomic scale (Supplementary, Materials S7). To illustrate how the SVO can be operationalised, we provide a matrix of equivalence factors reflecting the ratio of the SVO to the SCC for different duration and risk parameters and climate scenarios (Table 1). This equivalence can help to compare offsets of different qualities within the offset market. A calibration of the equivalence factor using observed data on offset impermanence, failure and additionality risks answers the central question: what is the value of an impermanent and risky offset compared to a permanent reduction in emissions? In the RCP2.6 emission scenario, the SVO of a 50 year project with a 0.5% (1%) likelihood of failing or becoming non-additional each year and has roughly 50% (30%) of the value of a riskless permanent project, given by the SCC. This means that between 2 and 3 such offsets are equivalent to a permanent ton of carbon removed. This rule of thumb should, however, should be carefully deployed. Failure rates and additionality risks are difficult to estimate precisely and vary across projects and providers. Offsets with equivalence greater than 3 due to such risks are likely to be avoided.

Since the SVO is the value of delayed emissions, it has many other applications. We illustrate applications to Life Cycle Analysis of carbon (wood pellets versus fossil fuels) and carbon debt payments, each of which require the comparison of time paths of emissions and storage, delaying of emissions or emissions reductions into the future.

Previous approaches appear in high-level policy documents such as the IPCC special report on land use change[17], international guidelines for carbon footprinting and Life Cycle Analysis[17,18], and guidance on commercial carbon crediting and offsets strategies (e.g. CarbonPlan). Supplementary Table S1 in S1 categorises the shortcomings of previous approaches and illustrates how they disagree in their assessment of temporary emissions reductions: a temporary project of 50 years is valued at between 0% to 90% of the value of a permanent storage depending on the approach taken. The SVO advances this body of work and will be useful for practical policy purposes.

The effect of a temporary carbon offset on the climate

We embed our analysis of temporary emissions reductions in recent climate models. Figure 1 shows the temperature effect of a temporary withdrawal of one unit of CO2 in 2020 which is released back into the atmosphere in 2070. The green bands show the deciles of 256 combinations of carbon absorption and thermal inertia models in the CMIP 5 modelling ensemble. It also shows the result for the FAIR model which adds the feedback that warmer and more acid seas will absorb less CO2. The graph shows that a CO2 withdrawal has a rapid cooling effect, which is more or less constant over time and stops rapidly after the CO2 is reinjected in the atmosphere after 50 years. These climate dynamics allow us to approximate the temperature response in Figure 1 by a step-function with a delay of period ξ between absorption and the temperature effect. From our own calculations, the best fit for ξ is $\xi = 3$ years for the SSP1-RCP2.6 scenario. The step-function with a delay of ξ is in line with the common assumption that warming ($T_{t+\xi}$) is proportional to cumulative CO2 emissions (S) between the pre-industrial period and time t: $T_{t+\xi} = \zeta S_t$, where ζ is the Transient Climate Response to cumulative Emissions (TCRE) ([19,20]). The Supporting Materials (S2) show the impacts for atmospheric CO2 concentrations and (S3) for other emissions scenarios. Only one previous contribution has considered the temperature response in relation to impermanence, but only to focus on the increase in temperature at the point of CO2 re-release (here 2070), ignoring the prior reduction in temperatures and the associated economic value of reduced damages[1]. The underlying climate dynamics are important. Some of our analysis would have to be augmented to consider greenhouse gases with different climate dynamics.

The Social Value of Offsets (SVO)

The Social Cost of Carbon (SCC) is the economic valuation of the damages caused by the marginal additional ton of CO2 to the atmosphere, or alternatively the benefit of a permanent reduction of CO2 in the atmosphere. An impermanent offset will remove CO2 from the atmosphere for a limited duration. The Social Value of an Offset (SVO) depends on the damages prevented by, or expected to be prevented by, this temporary or risky removal of CO2 from the atmosphere. The SVO is therefore closely related to the Social Cost of Carbon (SCC) and reflects the value of delaying emissions. To characterise the SVO we use a damage function, $D(T,Y)$, which depends on the size of the economy (GDP), Y, and is convex and increasing in temperature, T, in line with recent research[21,22]. A unit of emissions at time τ will add a marginal damage ζD_T (subscripts denote partial derivatives and ζ is the TCRE) with a delay ξ from time $\tau+\xi$ onwards. In a warming world, the marginal damage as a result of an emission at time τ will increase over time. The SCC at time τ, SCC_τ, is defined as the sum of the discounted marginal damages from $\tau+\xi$ into the infinite future.

$$SCC_\tau = \sum_{t=\tau}^{\infty} exp\left(-r\left(t+\xi-\tau\right)\right)\zeta D_{T_{t+\xi}} \tag{1}$$

An impermanent offset

If an offset were to remove 1 ton of CO2 from the atmosphere permanently at time τ, its social value would be SCC_τ. However, permanence and certainty are not characteristics of the typical offset offering[9]. Assume, therefore, that an offset removes 1 ton of CO2 at time τ_1 until this 1 ton of CO2 is re-released at time, τ_2. The SVO in this case is the present value (valued at date $t=0$) of the damages avoided for time horizon $\tau_1+\xi$ to $\tau_2+\xi$:

$$SVO_{\tau_1\tau_2} = \sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{\zeta D_{T_{t+\xi}}}^{Marginal\ damages} \tag{2}$$

Provided that marginal damages are strictly positive, the SVO is always positive, contrary to claims in the previous literature that it is zero or negative[1,3,4,23]. We will elaborate on why zero valuations appear in the literature. For further intuition, note that SVO reflects the net benefit of a permanent emissions reduction at time τ_1 minus the damages caused by the re-release of emissions at time τ_2. The $SVO_{\tau_1\tau_2}$ is therefore the difference between SCC_{τ_1} and SCC_{τ_2} in present value terms. Define x_1 and x_2 as the average growth rate of SCC_τ until τ_1 and between τ_1 to τ_2 respectively. The Materials and Methods section shows that the SVO is then:

$$SVO_{\tau_1\tau_2} = SCC_0\ \overbrace{e^{(x_1-r)\tau_1}}^{Delayed\ start} \overbrace{\left(1-e^{(x_2-r)(\tau_2-\tau_1)}\right)}^{Impermanence} \tag{3}$$

$SVO_{\tau_1\tau_2}$ is a corrected version of the value of a permanent reduction in emissions today, SCC_0, where the correction factor reflects: i) the delay in implementation from today until τ_1 ; and, ii) the known end point and re-release of emissions from the project at time τ_2. The SVO formula in (3) is valid for any trajectory of marginal damages as long as $x_2 < r$, which is proven to be the case in the Supporting Materials (S4) for optimal and non-optimal scenarios.

An offset with failure risk

The analysis is extended to take into account the likelihood that at any moment the offset technology could fail, e.g. reforestation or avoided deforestation is destroyed by force majeure (fire or disease), property rights failure or a change in land-use policy in situ. Suppose that, for contractual reasons say, the offset remains temporary with a known fixed end date τ_2, and is subject to the constant instantaneous hazard rate, ϕ, reflecting the instantaneous probability of an offset failing at time τ, conditional on having already survived until that date. The probability that at any future time τ the offset project continues to provide one ton of emissions reduction is $P(t \geq \tau) = \exp(-\phi\tau)$, or else has failed to offset is $1-\exp(-\phi\tau)$. The duration of the offset is therefore uncertain but $\tau_2 - \tau_1$ is the maximum. The Materials and Methods section shows that if SCC_τ increases at rates x_1 and x_2, the SVO requires an additional correction factor to reflect this failure risk:

$$SVO^{\phi}_{\tau_1 \tau_2} = SCC_0 \overbrace{e^{(x_1 - r)\tau_1}}^{Delayed\ start} \overbrace{\left(1 - e^{(x_2 - r - \phi)(\tau_2 - \tau_1)}\right)}^{Impermanence} \overbrace{\frac{r - x_2}{r + \phi - x_2}}^{Failure\ risk} \tag{4}$$

The Supporting Materials (S5) provides closed-form solutions for the SVO assuming linear and exponential temperature paths, when the SCC does not necessarily grow exponentially at rates x_1 and x_2.

An offset with non-additionality risk

Another aspect of project risk is the risk of non-additionality: that a project adds nothing compared to the counterfactual without the project. The time profile of 'additionality risk' depends on the type of project. If a project removes CO2 from a baseline in which there was no removal, such as a reforestation project, there is a risk that in the absence of the project reforestation would have occurred anyway, e.g. if forests become more productive than barren land, due to policies that existed anyway, or due to secondary forest regrowth[24]. In this case additionality risk corresponds to an earlier end of the project, very similar to the risk of failure, as shown in panel (b) of Figure 2. In this context, the risk of non-additionality can be framed as a hazard rate φ, leading to the probability $P(t \geq \tau) = \exp(-\varphi\tau)$ that the project is additional (has a causal effect) at least until time τ. The expression is analogous to the case of a failure risk where the discount rate becomes $\phi + \varphi$ and the correction factor becomes $\frac{r-x_2}{r-x_2+\phi+\tilde{\varphi}}$ (see Materials and Methods for a proof). Note that our formula is also valid if ϕ and φ are both time dependent yet their sum is constant, reflecting the intuitive case where degradation of a forestry project is more likely early on, and reforestation in the baseline is more likely further in the future.

Alternatively, conservation projects take as their baseline ongoing loss of forested land, and offsetting stems from avoided deforestation, under the assumption that in the baseline CO2 would have been emitted, but the project avoids these emissions. Here non-additionality occurs at the start of the project since the expected deforestation potentially would not have happened in the baseline, as depicted in panel (c) of Figure 2. Assume that without the preservation project, there is a hazard rate $\tilde{\varphi}$ that the forest would have disappeared, making the offset additional. The probability that the project has an additional (or causal) effect at time τ is therefore: $P(t \leq \tau) = 1 - \exp(-\tilde{\varphi}\tau)$. The Materials and Methods section shows that the correction factor now becomes $\left(\frac{r-x_2}{r-x_2+\phi} - \frac{r-x_2}{r-x_2+\phi+\tilde{\varphi}}\right)$ for sufficiently large τ_2.

A general formula for equivalence

The analytical formulae for the SVO have deployed simplifying assumptions for expositional purposes, namely, the instantaneous absorption and later release of carbon and the exponential growth rate of the SCC. The Materials and Methods provides a general formula for the SVO which accommodates any pathway of absoption and release at each point in time (q_t) and any pathway for emissions and hence temperature (T) and damages. The formula also embodies an explicit quadratic damage function. Due to its flexibility, the general formula is recommended for practical purposes since it allows the user to insert the desired emissions/temperature pathway and profile of absorption and release. The general formula is presented as the ratio of the SVO and the SCC and can be viewed as a correction factor reflecting the equivalence between the project under evaluation and a permanent removal technology. One key advantage of this formula is that the practitioner need not take a position on two difficult-to-estimate parameters: the TCRE (ζ) and the marginal damage parameter (γ), both of which cancel. Table 1 reports the resulting equivalence factors for different parameters and RCP scenarios, where an adjustment factor of 40% means a particular project is equivalent to only 40% of a permanent removal technology, and 2.5 of such 1-ton offsets would be required to offset 1 ton of emissions. This equivalence factor is a key contribution of this research. S 7 extends the analysis to a stochastic formula and discusses correlations between uncertainty on temperatures, consumption and failure rates.

Applications of the SVO

The SVO has many applications. The Materials and Methods provides a calibration of the SVO equivalence to real world risk parameters using proxy estimates of failure and additionality risk (e.g. appropriation risk, property rights risks, buffers for forests). The calibration estimates failure/non-additionality risks of between 0.5% and 1% per year, and equivalence of 50 year storage of approximately between 40% and 33%: between 2.5 and 3 such 1-ton offsets are equivalent to 1 ton permanently removed. Care is needed in applying this general equivalence too broadly, since more research is needed to obtain precise estimates in any given context, while additionality risk is extremely difficult to estimate ex ante. A general rule of thumb might be an equivalence of between 50% and 33%, so between 2 and 3 offsets for every permanent ton. Yet, in some risky cases, equivalence may be closer to 0%, and equivalence of less than 30% would probably be avoided in the offset market.

Nevertheless, the ability to calculate equivalence suggests an institutional mechanism to counter the risk of non-additionality. Current contracts, where 1 ton stored compensates 1 ton of emissions, imply additionality over millenia, given the virtually perpetual temperature effect of emissions. Temporary offsets contracts are much more credible. Knowing that 3 tons absorbed for 50 years (at reasonable risk) is equivalent to 1 ton permanently absorbed, means a contract for storing 3 tons for 50 years is equivalent to the perpetual contract for one. After 50 years, a new contract can be signed for the same 3 tons if additionality is proven.

Since the SVO captures the value of temporary storage of carbon, it has several policy applications beyond the valuation of offsets. Firstly, the SVO allows the benefit-cost ratio of offsets or temporary storage solutions to be calculated and compared to alternative technologies for mitigating climate change. This can inform the efficient deployment of technologies to combat climate change. Second, the general SVO formula is applicable to many situations where temporary storage or cycles of emissions and sequestration occur. It can therefore be an input to Life-Cycle Analysis (LCA). The Materials and Methods applies the SVO formula to an LCA of biofuels carbon following the examples of[27] and[5]. When biomass production starts with old growth forest, the advantage of biofuels falls from 50% when using GWP to 7% using the SVO approach due to its updated treatment of climate science and economics. Third, the price of carbon-debt: the social cost of renting atmospheric storage now (debt) to be offset with negative emissions later (repayment), can be calculated using the SVO formula. Given a 1:3 rule of thumb, a company which emits a ton today and commits to a permanent removal in 50 years time, would pay 33% of the carbon price today to cover the damages of temporary atmospheric storage. The up front payment provides climate finance and incentives to abate emissions rather like a carbon tax. The Materials and Methods section provides more details.

A Cost-effectiveness valuation framework does not value the delayed damages

Climate change mitigation is frequently viewed in terms of Cost-Effectiveness Analysis (CEA), which minimizes abatement costs to keep warming below a target level. For instance, the carbon price in the UK reflects the marginal abatement cost of meeting a net zero target by 2050, motivated by the 1.5C target of the Paris Agreement. The CEA valuation framework is a useful climate policy tool because it is often easier to agree on a temperature target than to agree on the size of damages and/or the discount rate[28]. However, in the evaluation of temporary removal of carbon, the CEA valuation framework is problematic.

Technically, a feature of a cost-minimising abatement strategy is that the price of carbon increases at the discount rate, prior to hitting the constraint. This is a manifestation of the Hotelling Rule. Using $x = r$ in Equation (3) yields a zero value for a temporary carbon removal. This case is reflected in the previous 'economics' strand of the literature[3,4]. The intuition here is that because the carbon price in the CEA framework rises at the rate of discount, the present value of the carbon price is the same for all horizons. Therefore, before hitting the temperature constraint, the value of a reduced emission today is perfectly cancelled by the cost of re-emission in the future. By contrast, our Equation 2 and Supporting Materials (S4) show that the welfare impact of delayed damages cannot be zero. The zero-valuation result in CEA should not be interpreted as an indication that offsets have no value, but rather that the valuation framework is not appropriate for the job. CEA minimises costs but does not maximize welfare, therefore the welfare value of delaying damages is ignored.

In the Cost-Benefit framework of the SVO, delayed damages are valued by reference to the trajectory of the SCC. In the S4 we show in a simple model that the SCC always increases at a rate that is lower than the discount rate: $r > x$. The SCC grows slower than the discount rate, hence the benefit of reducing emissions is only partially cancelled by the cost of emitting in the future. Delayed emissions therefore have a positive value. However, the Supporting Material (S10) also shows that CEA can overvalue projects if they extend beyond the point at which the target is met, since from this point onwards the carbon price remains constant ($r > x = 0$). The constant carbon prices found in previous economic approaches[3,4] are not a feature of most climate-economy models. In sum, CEA can either under- or overvalue delayed emissions. However, in the case where cost-effectiveness models include damages and are set up as a cost-benefit analysis with a temperature constraint, Equations 2 and 3 still apply, although the SVO will be higher and equivalence factor lower (see S4 for a proof).

Conclusion

While the IPCC note that meeting the objectives of the Paris Agreement will require some offsetting and Nature Based Solutions, some organisations (e.g. the Science Based Targets Initiative) suggest that offsetting should be largely avoided due to the unregulated, impermanent and risky nature of the offset market. However, the approach outlined in this paper illustrates that in principle delaying emissions, even when offset projects are temporary and risky, is valuable in welfare terms. The Social Value of Offsets formalises this point so that the question of whether offsets should form a part of a net-zero or Paris compliant strategy becomes an empirical one. To fully characterise the SVO more data is required from offset suppliers on the impermanence, failure and non-additionality of offset projects. While our estimate that between 2 and 3 temporary (50 year) offsets are equivalent 1 ton of emissions needs further grounding, the SVO provides a framework of analysis to establish equivalence and hence comparability of different offset projects. Of course, the social value of nature-based carbon offsets may well be much higher because of the co-benefits of biodiversity and ecosystem service provision. The benefits of delayed emissions measured by the SVO then need to be weighed against the costs of provision (e.g. costs of land). Furthermore, abatement as an alternative to offsetting may come with gains from innovation that arise when projects realized today reduce the cost of similar projects in the future, via learning-by-doing, scale or network effects (e.g. renewable energy). This is also true for hi-tech offset solutions (e.g. geological storage), although gains from innovation in nature-based solutions cannot be ruled out. With those possible extensions in mind, the SVO can play an important role in the consistent appraisal of net-zero climate policy and harmonising the offset market.

Materials and Methods

Proof of equivalence between Equation (2) and Equation (3)

Assume that the social cost of carbon is finite. Adding and subtracting the same sum over $[\tau_2, \infty]$ in Equation (2) and multiplying by $exp(-r\tau)$ outside the sum and by $exp(r\tau)$ inside the sum, we obtain:

$$SVO_{\tau_1\tau_2} = exp(-r\tau_1) * \sum_{t=\tau_1}^{\infty} exp(-r(t+\xi-\tau_1))\,\zeta D_{T_{t+\xi}} - exp(-r\tau_2)\sum_{t=\tau_2}^{\infty} exp(-r(t+\xi-\tau_2))\,\zeta D_{T_{t+\xi}} \tag{5}$$

Given the definition of SCC_τ in (1), $SVO_{\tau_1\tau_2}$ simplifies to:

$$SVO_{\tau_1\tau_2} = exp(-r\tau_1)\,SCC_{\tau_1} - exp(-r\tau_2)\,SCC_{\tau_2} \tag{6}$$

$SVO_{\tau_1\tau_2}$ is simply the difference between the present values of SCC_{τ_1} and SCC_{τ_2}. Define x_2 as the mean growth rate of the SCC between time τ_1 and τ_2 (x_2: $SCC_{\tau_2} = SCC_{\tau_1} exp(x_2(\tau_2-\tau_1))$), and x_1 as the mean growth rate of the SCC between τ_0 and τ_1. Substituting out SCC_{τ_1} and SCC_{τ_2}in Equation (6) results in Equation (3).

Note that if marginal damages increase faster than the discount rate in the long run, Equation (1) shows that the social cost of carbon is infinite. As a result, Equation (3) cannot be used but Equation (2) remains valid. Equation (2) shows that the SVO is positive, contrary to van Kooten's claim[4] that the value of an offset is zero when marginal damages increase faster than the discount rate (p 459). In essence, the present value sum of marginal damages avoided is always positive, but the difference between two infinite values (SCC_{τ_1} and SCC_{τ_2}) is not well defined.

Proof of relationship between marginal damages growth and SCC growth

For notational convenience we will switch to continuous time. If the marginal damages increase exponentially at rate x, the SCC at time τ is:

$$SCC_\tau = \int_{t=\tau}^{\infty} \exp(-r(t+\xi-\tau))\,\zeta D_{T_{\tau+\xi}} \exp(x(t-\tau))\,dt$$

where $D_{T_\tau}$is the marginal damage at time τ. The SCC at time τ can then be re-written as:

$$SCC_\tau = \frac{\exp(-r\xi)}{r-x}\zeta D_{T_{\tau+\xi}} \tag{7}$$

from which it follows that:

$$SCC_\tau = \frac{\exp(-r\xi)}{r-x}\zeta D_{T_{0+\xi}} e^{x\tau} = SCC_0 e^{x\tau} \tag{8}$$

In the case of the seminal model by[29] model or[30], x corresponds to the growth rate of GDP. When climate damages are quadratic and are proportional to GDP, x corresponds to the growth rate of GDP plus the growth rate of temperature.

Derivation of SVO with failure risk

By multiplying each time period with the probability that the project has not failed $e^{-\phi(t-\tau_1)}$ Equation (15) becomes:

$$SVO^{\phi}_{\tau_1\tau_2} = \exp(-r\tau_1)\int_{t=\tau_1}^{\tau_2} \exp(-(r+\phi)(t-\tau_1)-r\xi)\,\zeta D_{T_{t+\xi}}\,dt$$

In the case of exponentially increasing marginal damages $D_{T_{t+\xi}} = D_{T_{\tau+\xi}} e^{x_2(t-\tau)}$, where again, x_2: $SCC_{\tau_2} = SCC_{\tau_1} exp(x_2(\tau_2 - \tau_1))$, and x_1: $SCC_{\tau_1} = SCC_0 exp(x_1 \tau_1)$, we obtain an exponential function in the integral, which we can solve

$$SVO^{\phi}_{\tau_1 \tau_2} = \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} \int_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi-x_2\right)\left(t-\tau_1\right)\right) dt \tag{9}$$

$$= \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} \left[\frac{1-\exp\left(-\left(r+\phi-x_2\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi-x_2}\right]. \tag{10}$$

We can now write the result as a function of the SCC using Equation (7)

$$SVO^{\phi}_{\tau_1 \tau_2} = SCC_{\tau} \exp\left(-r\tau_1\right)\left[1-\exp\left(-\left(r+\phi-x_2\right)\left(\tau_2-\tau_1\right)\right)\right] \frac{r-x_2}{r+\phi-x_2}. \tag{11}$$

From here the formula in the text follows assuming that the SCC grows at a rate x_1 between $t = 0$ and $t = \tau_1$ and x_2 between $t = \tau_1$ and $t = \tau_2$. This result also holds for constant marginal damages, i.e. for $x = 0$. The Supporting Material (S7) derives formulas for other paths of marginal damages.

Derivation of SVO with additionality risk

Additionality risk is taken into account by multiplying each period by the probability $\left(1-e^{\tilde{\varphi}(t-\tau_1)}\right) e^{-\phi(t-\tau_1)}$ where ϕ is the hazard rate for both project failure and non-additionality at the end and $\tilde{\varphi}$ governs the risk of non-additionality at the start. Equation 4 now becomes

$$SVO^{\phi,\tilde{\varphi}}_{\tau_1 \tau_2} = \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} * \int_{t=\tau_1}^{\tau_2} \exp\left(-\left(r+\phi-x_2\right)\left(t-\tau_1\right)\right) - \exp\left(-\left(r+\phi+\tilde{\varphi}-x_2\right)\left(t-\tau_1\right)\right) dt \tag{12}$$

$$= \exp\left(-r(\tau_1+\xi)\right) \zeta D_{T_{\tau_1+\xi}} * \left[\frac{1-\exp\left(-\left(r+\phi-x_2\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi-x_2} - \frac{1-\exp\left(-\left(r+\phi+\tilde{\varphi}-x_2\right)\left(\tau_2-\tau_1\right)\right)}{r+\phi+\tilde{\varphi}-x_2}\right] \tag{13}$$

We can now write the result as a function of the SCC using Equations 7 and 8

$$SVO^{\phi,\tilde{\varphi}}_{\tau_1 \tau_2} = SCC_0 \overbrace{\exp\left(-\left(r-x_1\right)\tau_1\right)}^{Delayed\ start} \overbrace{\left(1-\exp\left(-\left(r+\phi-x_2\right)\left(\tau_2-\tau_1\right)\right)\right)}^{Impermanence} * \left[\overbrace{\frac{r-x_2}{r+\phi-x_2}}^{\substack{Failure\ risk\ or \\ Additionality\ at\ end}} - \overbrace{\frac{r-x_2}{r+\phi+\tilde{\varphi}-x_2} \frac{1-\exp\left(-\left(r+\phi+\tilde{\varphi}-x_2\right)\left(\tau_2-\tau_1\right)\right)}{1-\exp\left(-\left(r+\phi-x_2\right)\left(\tau_2-\tau_1\right)\right)}}^{Additionality\ risk\ at\ start}\right] \tag{14}$$

Note that ϕ slightly increases our 'early end' factor, because the project may fail before time τ_2 in which case the impermanence becomes irrelevant. Similarly, the second factor in the 'additionality risk at start' term reduces the effect of impermanence (τ_2), taking into account that if the project does not start before τ_2, the impermanence is irrelevant. Therefore, for combinations of τ_2 and $\tilde{\varphi}$ which make it unlikely that the project never starts, the correction factor for additionality risk will converge to $\left(\frac{r-x_2}{r+\phi-x_2} - \frac{r-x_2}{r+\phi+\varphi-x_2}\right)$.

A general formula for the SVO

While providing a straightforward exposition of the principles underpinning the SVO, the assumption that the SCC grows at a constant rate x does not necessarily reflect typical climate scenarios, such as the IPCC's Representative Concentration Pathways (RCP). In this section we generalise the SVO formula to allow for any any temperature path and an explicit characterisation of climate damages, and consequently different trajectories for the SCC. The general formula also provides more detailed project specific characteristics, to account for the gradual absorption and re-release that typifies many nature-based and other solutions to climate change.

We model climate damages proportional to GDP, Y, and quadratic in temperature: $D = Y\left(1-\exp\left(-\frac{\gamma}{2}T^2\right)\right)$[21], the marginal damage for a unit of CO2 emission at time t is linear: $\zeta D_T = \zeta\gamma YT$. This is a typical assumption in Integrated Assessment Models (IAM, e.g. DICE) deployed for analytical convenience here, yet does not preclude the use of other damage functions. Further, suppose that absorption and release of CO2 is reflected by a time profile q_t indicating the stock of carbon absorbed by the successful project by time t, rather than the step-function used so far. With these generalisations the formula for the SVO correction factor accounting for impermanence, failure and non-additionality risks becomes:

$$\frac{SVO^{\phi,\varphi}_{\tau_1\tau_2}}{SCC_0} = \frac{\sum_{t=\tau_1}^{\tau_2} \overbrace{e^{-r(t+\xi)}}^{Discount\ factor} \overbrace{e^{-(\phi+\varphi)(t-\tau_1)}}^{\substack{Failure\ and\ additionality \\ risk\ at\ end}} \overbrace{\left(1-e^{-\tilde{\varphi}(t-\tau_1)}\right)}^{Additionality\ risk\ at\ start} \overbrace{q_t}^{Quantity\ stored} \overbrace{\zeta\gamma Y_{t+\xi}T_{t+\xi}}^{damages}}{\sum_{t=0}^{\infty} e^{-r(t+\xi)}\zeta\gamma Y_{t+\xi}T_{t+\xi}} \tag{15}$$

This flexible generalisation brings together both physical and economic determinants of the SVO and SCC in a coherent and transparent manner, and has a number of appealing features. Firstly, the two most difficult parameters to parameterise, the TCRE, ζ, and the damage coefficient, γ, cancel and therefore do not affect the offset correction factor. Of the climate and macro-economic determinants, only the future temperature and GDP paths are needed to operationalise this formula. The Supporting Materials (S6) extends the matrix to other RCP scenarios. Second, the formula easily accommodates further project specific factors, such as time dependence of the failure and non-additionality risks, and the Supporting Materials (S7) provide a deeper risk analysis when growth, temperatures and individual project risks are correlated. Finally, the linear approximation of cumulative emissions, temperature and damages reflected by ζ can easily be replaced by the *exact* time profile of the temperature impact response function in Figure 1.

Table 1 summarises the adjustment factors for a subset of parameter values and temperature paths. An offset of duration of 25 years with a 0.5% annual risk of failure or non-additionality has a correction factor of 23% in RCP 2.6 (1.8C), which drops to 16% in RCP 6 (3.1C), which has higher marginal damages in the future when the project releases its carbon back in the atmosphere. Note that in high emission scenarios although the conversion factor is lower, the absolute dollar value of an offset will be higher. Table 1 allows a careful comparison of absolute and relative values.

The concept of the SVO and the general formula provide an answer to the question of how much carbon should be held in offsets compared to alternative mitigation strategies. A correction factor of z means that in order to offset the equivalent of 1 ton of carbon $1/z$ offsets would have to be purchased. Table 1 shows that this can mean anything from a near one-to-one relationship between offsets projects and permanent carbon removal, to a situation where 10 offsets, each claiming to offset 1 ton of carbon, would have to be purchased to be equivalent to a permanent emissions reduction, when duration is short and risks are high. It is important to recognise that this equivalence is in welfare terms and in the aggregate. Given uncertainty, some projects will end up reducing emission by more than 1 ton in the end, others by less, but on average the overall impact would be a 1 ton emissions reduction. Table 1 makes the rate of conversion explicit. The SVO essentially values the social benefit of temporary carbon storage and delayed emissions. As such, the efficiency of offsets compared to alternatives can also be gauged by comparing offsets in terms of their benefit-cost ratios.

Applications of the SVO

Equivalence to 1 ton of CO2 emitted

Calibration of the SVO for duration τ_2, hazard risk of failure, ϕ, and additionality, φ, leads to a simple rule-of-thumb for the SVO correction factor. The chief failure risks concern fires and disease at the project level, and political risk (e.g. risk of property rights appropriation) at the macroeconomic level. In the absence of a comprehensive dataset of offset failure rates, we draw inference from related literature to shed light on failure risk. The Supplementary Materials (S8) show that observed and recommended buffers for failure of offsets imply values of $\phi = [0.001, 0.002, 0.01]$ for $\tau_2 = 50$, a reasonable period for regrowth, based on buffers ranging from 5 - 40%[31,32]. Estimated business risks (termination of contracts and political risks) imply $\phi = [0.01, 0.04]$, with higher rates in Asia, Latin America and Central and Eastern Europe compared to Europe and North America[33,34].

Additionality risk is difficult to estimate precisely.[12] estimate 90% additionality (10% leakage) in their randomized control trial of REDD+ projects in East Africa. Elsewhere, 40% of REDD+ projects were estimated to overlap with protected areas[35], or generally non-additional[11], meaning 60% additionality.[36] estimate 53% additionality (a 47% reduction in deforestation), also from REDD+ projects, Using 80 - 75% additionality as a central approximation implies $\varphi = [0.004, 0.006]$. Table 1 presents sensitivity analysis with $\varphi = [0.005, 0.01]$, the latter upper value potentially reflecting political risks. Non-forest offsets tend to have historically lower levels of additionality[10,37] (See S8). While 75-80% additionality is potentially optimistic, lower levels of additionality, once identified, are unlikely to be acceptable for future offsets.

Although not perfect (see[9]), buffer stocks can help manage the physical risks of individual nature-based projects and hence are a useful strategy to hedge observable failure risk in the future, meaning that estimating the failure risk parameter ϕ may be unnecessary. However, buffers do not address additionality risk, which is often unobservable. Political and additionality risks therefore remain the chief concerns in the calculation of the SVO. Table 1 shows the equivalence factors for different RCP2.6 and RCP6.0, and for additionality risk 'at the end' (see Figure 2(b) ranging from 0 to 0.01, and additionality risk 'at the beginning' (see Figure 2(c) ranging from low ($\tilde{\varphi} = 1000$ with 100% chance of additionality) to high ($\tilde{\varphi} = 0.25(0.5)$ with 70% (90%) chance of additionality after 5 years). This preliminary calibration reflects a reasonable range based on political risk and additionality discussed above, geographical variations in political and additionality risks, and variation across the possible climate scenarios (RCPs). Table 1 shows that that for a 50 year offset a plausible range for the correction factor lies between between approximately 50% for low risk projects and 30% for riskier ones. This equates to between 2 and 3 temporary offsets being equivalent to one permanent one, or a permanent reduction in emissions. The range of 2-3 constitutes a practical rule-of-thumb for the implementation of the SVO for forest-based offsets. While Table 1 indicates that in certain circumstances (RCP 6.0, with $\varphi = 0.01$ and $\tilde{\varphi} = 0.25$) the correction factor is a mere 13%, meaning an equivalence of approximately 8, it is likely that beyond an equivalence of 3, the risks or costs associated with an offset project are too high to be worthwhile investing in. An analogy can be found in highly risky financial assets that are considered junk. The SVO can be used to both filter acceptable and unacceptable offsets, and then establish equivalence for those with an acceptable level of risk or duration.

Non-permanent contracts

A 1:2 or 1:3 equivalence between emitted tons and forestry offset storage over 50 years opens up the possibility of finding temporary contracts (for 50 years say) to replace eternal ones. The current practice in the voluntary market is to assume that each ton is stored eternally, with the responsibility to uphold this commitment lying with the forest manager. A 50 year commitment is more realistic to administer, being analogous to 50 year Treasury Bonds for instance. With the correction factor reflecting impermanence and additionality risk the forest managers' responsibility to society is complete after 50 years, having sequestered between 2 and 3 tons within that period. At the end of the contract the same forest can receive credits again for a new cycle of 50 years, provided that additionality can be proven based on past experience and current trends in deforestation and policy. The approach also improves on current CDM practice, where an emission leads to an implicitly eternal liability: a ton emitted today requires a new CDM forestry project of one ton every 20 years. Additionality risks and the eternal liability structure have precluded forest-based offsets from being included in compliance mechanisms such as the EU ETS, and led to only a small proportion of CDM projects being nature-based. Shorter contracts organized around the SVO could reduce these uncertainties, increase eligibility and potentially increase the supply of nature-based offsets.

Life Cycle Analysis (LCA)

LCA of carbon compares the carbon emissions of different activities (energy production, agriculture, etc.) to guide climate policy. Consider for example burning wood pellets for home heating. Burning pellets releases one ton of CO2 , a forest carbon sink is reduced by one ton, but gradually replenished thereafter. The SVO and correction factor help gauge whether the cycle of emissions and storage associated with pellets is better than burning fossil fuels over their lifetimes. In terms of the SVO formula q_t is now the reduced stock of forest biomass when pellets are burnt, which gradually tends to zero over time as the forest regrows. The Supporting Material (S8) reviews the contributions of[27] and[5] and shows if biomass production starts with old growth forest, wood pellets only have a 7% advantage compared to fossil fuels using the SVO approach, compared to 50% when typical LCA methods such as Global Warming Potential are used (see alternatives in Supplementary Table S1) . This difference arises from the accurate treatment of the physical and economic aspects of the dynamic cycle of delay and growth that determines the emissions path, temperature and climate damages.

Temporary atmospheric storage and carbon liabilities

The SVO approach values the temporary storage of carbon, but can be adapted to value the cost of temporary storage in the atmosphere and 'carbon debt': the cost of emitting now and reducing emissions later. A carbon liability or 'debt' is an important financing mechanism in a net-zero world where revenues from carbon taxes are insufficient to fund the massive

(10% of world GDP in[6]) investment in climate mitigation required to comply with the 1.5C target. If companies emit today under the agreement that they remove the carbon at some future date, there are two elements to the liability: the cost of the future emissions reduction and the damages caused until the debt matures. The SVO formula can value the damages of this temporary atmospheric storage by interpreting q_t in Equation 4 as the additional carbon stored in the atmosphere and using the temperature response function for a temporary release of carbon. Supplementary Fig. S9a in S9 shows the impact of temporary emissions on temperatures. The resulting Social Cost of Atmospheric Storage (SCAS) defines the rental cost of atmospheric storage in terms of the damages caused, rather than using arbitrary interest payments as in[6]. Yet, the fundamental difficulties with carbon debt are: i) the commitment periods are much longer than the standard commitment periods of financial debt; and, ii) debt holders going bankrupt before the debt matures leading to carbon default. These issues are reduced if the SCAS is paid in full up front, although bankruptcy remains an issue. Given a 1:2.5 rule of thumb, a company which emits a ton today and commits to a permanent removal in 50 years time, would pay 40% of the carbon price to cover the damages of the the temporary atmospheric storage. Up front payment of the SCAS provides finance and proper incentives to abate emissions rather like a carbon tax (See Supporting Material, S8).

The Supplementary Materials (S8 and S9) provide more details on the calibration and each of these case studies.

Data and Code Availability Statement

The code and data used to create the Figures, and the Excel spreadsheet that underpins the Tables is available at the following github repository: https://github.com/BenGroom/socialvalueofoffsets.git.

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Competing Interests Statement

The authors declare no competing interests

Author Contribution Statement

FV and BG contributed 75% and 25% to the theory respectively. On all other aspects the contribution was equal.

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IPCC Scenario	Risk at start	Risk at end	SVO Correction factors (max.duration, v)				SCC ($\$/tCO_2$) Damages ($\gamma$)	
(Temp in 2100)	$\tilde{\varphi}$	$\phi+\varphi$	25	50	100	∞	γ=0.0077	γ=0.0025
RCP 2.6	1000 (low risk)	0	24%	44%	70%	100%	109	35
(1.8°C)		0.005	22%	39%	57%	70%	109	35
		0.01	21%	34%	47%	53%	109	35
	0.5	0	23%	43%	69%	99%	109	35
		0.005	22%	38%	56%	69%	109	35
		0.01	20%	34%	46%	52%	109	35
	0.25 (high risk)	0	22%	42%	68%	97%	109	35
		0.005	20%	37%	54%	67%	109	35
		0.01	19%	32%	44%	50%	109	35
RCP 6.0	1000	0	17%	34%	64%	100%	161	52
(3.1°C)		0.005	16%	30%	50%	66%	161	52
		0.01	15%	26%	40%	48%	161	52
	0.5	0	17%	34%	63%	99%	161	52
		0.005	15%	30%	50%	65%	161	52
		0.01	14%	26%	40%	47%	161	52
	0.25	0	15%	33%	62%	98%	161	52
		0.005	14%	28%	48%	64%	161	52
		0.01	13%	25%	39%	46%	161	52
Uncertain RCP	1000	0	20%	38%	66%	100%	138	45
		0.005	18%	33%	51%	64%	138	45
		0.01	17%	29%	41%	46%	138	45
	0.5	0	19%	38%	66%	100%	138	45
		0.005	18%	33%	51%	64%	138	45
		0.01	17%	29%	41%	46%	138	45
	0.25	0	18%	37%	65%	99%	138	45
		0.005	17%	32%	50%	63%	138	45
		0.01	16%	28%	40%	45%	138	45

Table 1. Offset equivalence factors for non-permanence and risk: We assume a quadratic damages proportional to GDP $exp\left(-\frac{\gamma}{2}T^2\right)$ with damage parameters of[21] (Column 8) as well as[25] (Column 9). Temperature pathways evolve according to SSP1-RCP2.6; SSP4-RCP6.0 and an uncertain temperature path[26]. Other parameters are r=3.2%; $\tau_1 = 1year$; $\zeta = 0.0006°C/GtCO_2$; GDP growth=2%; $T_0 = 1.2°C$. We use Equation (15). For $\tilde{\varphi} = [0.5\ 0.25]$ the likelihood that the project is additional after 5 years is 92% and 71% respectively. For $\varphi + \phi = [0.005\ 0.01]$ the likelihood that the project is additional after 50 years is 78% and 61% respectively. Under uncertainty, we assume a temperature path following one of 3 RCP's (2.6, 3.4 or 6.0) with equal probability and a hazard rate with the same mean but increasing in temperature $\varphi_{uncertain} = \varphi_{certain}\left(0.5 + 0.5T/\bar{T}\right)$, where $\bar{T} = 2.01°C$, i.e. mean warming of the next 80 years in the 3 RCP's. Results for SSP4-RCP3.4 and SSP5-RCP8.5 are shown in S7.