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Misapplication of Conventional Economic Analysis to Climate Change From the Post-normal Science Perspective: The "Social Cost of Carbon" Myth

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A critical reflection over the latest comprehensive reporting efforts of the Intergovernmental Panel on Climate Change (IPCC) suggests that applications of cost-benefit analysis (CBA) to climate change, acts which importantly include the monetary calculation of the social cost of carbon (SCC), do not bring about the avoidance or mitigation of pervasive and irreversible climate change issues, issues which could likely continue on a multi-century to millennial time scale. This paper presents, first, a consideration of the most recent IPCC reports that indicated various contemporary problems and threats both to socioeconomic systems and ecosystems on this planet if and when CBA is uncritically applied to climate change issues. Following, a critical reexamination of three crucial concepts, namely, scarcity, discounting and substitution, is made in view of the roles they play in the theoretical foundation of conventional economics. Climate change is shown to be far beyond the scope of these concepts, hence far beyond the scope of CBA and the SCC approach. A discussion of a general alternative approach to addressing climate change issues is presented—one grounded in post-normal science that acknowledges the critical role deep uncertainty plays in many aspects of climate change issues. Reflecting on the need for such an approach and the shortcomings of past, conventional approaches suggests that establishing a process of social resolution of fundamental problems, including participation and mutual learning among relevant stakeholders, rather than a definite solution or technological implementation, is absolutely necessary. A critical study on many aspects of uncertainty is required for reaching constructive disagreement among stakeholders

Keywords: economic scarcity, discount rate, resource substitution, cost-benefit analysis, climate change, net primary productivity (NPP), social cost of carbon (SCC)

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INTRODUCTION

A well-known textbook by Samuelson and Nordhaus (2010, p. 4) states that economics is "the study of how societies use scarce resources to produce valuable goods and services and distribute them among different individuals". The authors (*ibid.*) add context to their definition, pointing out that "goods are scarce and society must use its resources efficiently". In conventional economics, an efficiency criterion as such directs users of cost-benefit analysis (CBA) to adopt a project that maximizes the present monetary value of net economic benefits over a given period of time, following the selection of a certain discount rate.

The rationale behind the closely related and widely used social cost of carbon (SCC) approach, an approach wherein the analyst seeks to measure the net economic cost of an extra ton of carbon dioxide emissions, or equivalent, similarly reflects the conventional economic efficiency concept. Proponents of SCC offer to decision-makers and other concerned persons a monetary valuation related to climate change, a sort of rough material for collective discourse. Nordhaus (2017, p. 1518) claims SCC to be the "most important single economic concept in the economics of climate change", explaining it to underlie over $1 trillion in benefits in the United States alone.

To calculate the SCC, one or more of several large integrated assessment models are run for (1) a variety of socioeconomic scenarios, (2) input parameter sensitivity distributions, and (3) hypothetical discount rates. For each discount rate considered, the results of the modeling effort are averaged, customarily equally weighting the outputs of the model(s) used. The final SCC values that emerge can be found to vary dramatically both within and between reporting efforts established in the discourse. Take, for example, the social cost of carbon dioxide value estimates presented by EPA (2017) vs. those of IWG (2021). They vary by two orders of magnitude, following normative disagreement over model inputs. The full distribution of the unaveraged model outputs, as presented in those two documents, span several additional orders of magnitudes.

Sizeable value discrepancies aside and despite the established nature and apparent popularity of the SCC concept, there does not appear to exist significant serious discussion over whether or not, from the start, the concept and its underlying fundamental assumptions can be applied to climate change issues. This is worrisome. If a recent series of reports by the Intergovernmental Panel on Climate Change (IPCC, 2014, 2022; Rogelj et al., 2018) is to be considered reasonable and compelling, applying conventional economic approaches such as CBA or SCC to climate change is not only problematic but potentially dangerous. In this work, several fundamental problems with the SCC approach are identified, emerging from a critical evaluation of the basic, conventional assumptions that underlie it.

Section Essential Points of the IPCC Reports presents an overview of the IPCC reports insofar as they are able to describe a situation where conventional economic analysis cannot be applied. Section Critical Appraisal of the Scarcity, Substitution, and Discounting Cornerstones of Conventional Economics examines the fundamental concepts of *scarcity*, *substitution* and *discounting*, which are the three theoretical cornerstones of conventional economics. Section Critical Appraisal of the Scarcity, Substitution, and Discounting Cornerstones of Conventional Economics suggests that the concepts of scarcity, substitution and discounting *cannot* be applied in the conventional economic fashion when considering climate change. Section Search for a "Plan B" for Tackling Climate Change Problems in the Post-normal Science Era presents a "Plan B", potentially useful for dealing with climate change problems, where the stance of post-normal science (Funtowicz and Ravetz, 1990, 1993) can be gainfully applied. Section Conclusion concludes.

ESSENTIAL POINTS OF THE IPCC REPORTS

Climate Change 2022 (IPCC, 2022) and *Climate Change 2014* (IPCC, 2014), the former being the IPCC's most recent report on the vulnerability of social-economic and natural systems to climate change and the latter being the IPCC's most recent comprehensive report, make the points enumerated below. The picture that emerges from the joint consideration of these points is essential to understand as it frames the problem that the SCC approach seeks to address. Section Critical Appraisal of the Scarcity, Substitution, and Discounting Cornerstones of Conventional Economics departs from this understanding.

(1) Without a substantial reduction in greenhouse gas (GHG) emissions, perilous, irreversible anthropogenic climate change will occur.
(2) Climate change will increase the likelihood and intensity of extreme weather events, including high and low temperature anomalies as well as heavy precipitation events and droughts. Such changes will endanger ecosystems, widespread, and generate a set of pressures—often life or death situations—on low-income countries.
(3) Marine life in particular will be faced with an increasingly lethal trilemma of rising temperature, lowering oxygen, and rising acidity. Climate change will drive a reduction and redistribution of marine life, endangering, in sensitive regions, highly dependent communities.
(4) Rural areas in general will be forced to confront changes in water and food availability, often dramatic ones. Agricultural livelihoods will be threatened as a result.
(5) Deleterious impacts on urban areas, which are disproportionately of high economic importance, are similarly expected to increase, as caused by changes such as sea level rise, severe scarcities among key resources, and the spectrum of expected intensified extreme weather events.
(6) A multitude of climate change adaptation opportunities present themselves in response to the aforementioned anticipations, though the consequences of their implementation, advantageous and disadvantageous, vary widely between economic sectors.

The IPCC reports suggest, most importantly, that unless alternative, more "sustainable" primary energy sources associated with substantial reductions in GHG emissions replace fossil fuels, climate change can be expected to intensify and persist, perhaps for centuries to come. It will, among other effects, seriously threaten net primary production in the biosphere. Note that net primary production is the most immediate base for anthroposphere life, the determiner of essential primary industrial sectors such as the agriculture, fishery, and forestry sectors (Vitousek et al., 1986). Assuming them to be credible sources on the matter, the IPCC's most recent reports point toward an essential set of context issues, fodder for an informed discussion over whether the basic framework of conventional economics, by extension approaches such as CBA and related SCC (Rogelj et al., 2018), is prepared to address the issue of climate change.

CRITICAL APPRAISAL OF THE SCARCITY, SUBSTITUTION, AND DISCOUNTING CORNERSTONES OF CONVENTIONAL ECONOMICS

This section presents a serious reconsideration of scarcity, substitution and discounting—three concepts from conventional economics that underlie the SCC approach.

Scarcity

It could reasonably be stated that the fundamental concept in economics is scarcity. Nearly 90 years ago, Robbins (1932, p. 15) defined economics as "the science which studies human behavior as a relationship between ends and scarce means which have alternative uses". Despite decades of research, the concept of scarcity has yet to be considered, in conventional economics, to the degree necessary to know whether associated approaches, such as CBA and related SCC, can be meaningfully used to address problems of climate change.

Scarcity first gained traction as a theoretical pillar of economics in the 1860s. Increases in the material standard of living in recently industrialized Western Europe, most emblematically England, encouraged sentiments of self-interest there (Marshall, 1920). In tandem, ideas of perpetual, substantial economic growth found inroads—inroads that later accelerated in the industrial world post–WWII. The use of fossil fuel in transportation and industry became pervasive, intertwined, and all but inextricable. Humans came to take the boon of fossil fuels for granted, anticipating (Jevons, 1965) limitless economic growth ad infinitum. The limitless nature of humanity's wants found a basis in the concept of scarcity—according to what has become convention, scarcity refers to the gap between goods or services available and "limitlessly growing" wants (Samuelson and Nordhaus, 2010).

When confronted with a scarce good or service, a decision to "efficiently allocate" is, by convention, made. CBA is typically applied to determine a course of action that purportedly maximizes the present monetary value of net economic benefits between some given initial point in time to some given end point in time. The conventional concept of scarcity is hence "moderate scarcity"—scarce goods and services are scarce in a relative sense, scarce in comparison to limitless wants and assumed to be sufficient for the most basic needs of humans. A prime example of the assumption that scarcity is moderate is Arrow and Debreu's (1954) influential article "Existence of an Equilibrium for a Competitive Economy", where the authors assume that a positive stock of each of a set of commodities would remain, for trading on the market, after a set of economic agents with the feasible ability to do so draw from that set of commodities.

On the other hand, severe resource scarcity is a notable reality when considering intragenerational distribution of resources. Consider **Figure 1**, which is a conceptual illustration of the intragenerational problem of equity.

(1) For each of three individuals, *A*, *B*, and *C*, corresponding relations of demand over the period *t*, D_{At}, D_{Bt}, and D_{At}, are shown. Note that the resource demanded is exhaustible.
(2) The dashed line, $D_{At+Bt+Ct}$, represents the aggregate demand of the three individuals considered, over the same period of time *t*.
(3) The four MC_i ($i = 1, 2, 3$, and 4) lines represent marginal cost lines. Taking line MC_1 as example, the resource allocated to each of the three individuals is R_{At}, R_{Bt}, R_{Ct}, respectively.

Even in this situation of moderate scarcity, R_{Ct}, allocated to *C*, is the largest amount of the resource among the three individuals. If the marginal cost line is situated between MC_3 and MC_4 then neither *A* nor *B* can afford, at all, to obtain the exhaustible resource. *A*'s demand as well as *B*'s demand is smaller than *C*'s demand at any price level due to insufficient income for *A* and *B*. In such a context, the market mechanism cannot provide individuals *A* and *B* with a satisfactory share of the resource considered—not satisfactory in the sense the resource may be vital but insufficient amounts of it supplied. That condition corresponds to a situation of "severe scarcity" in the sense the resource is scarce relative to indispensable need, not simple, "convenience-driven" demand (Hubin, 1989). When an economic community is presented with a situation of severe resource scarcity, a *socially agreeable arrangement* grounded in a framework of ethics is needed to ward off the worst of social-economic inequality. There are many possible arrangements. The quantity of persons obtaining the minimally satisfactory amount of the resource could be maximized, for example, or the resource could be equally distributed among all concerned people. The climate change discourse indicates many situations where severe scarcity must be seriously considered.

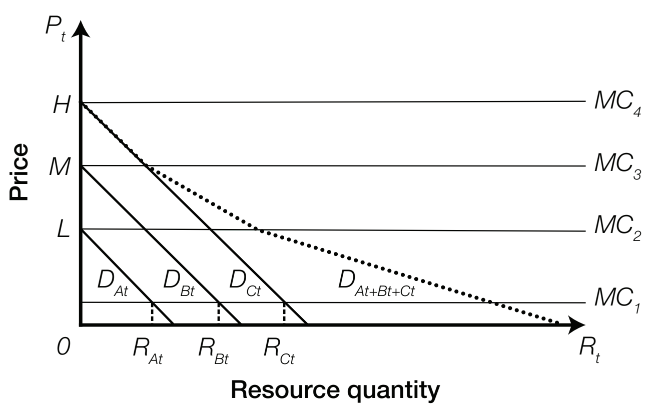

FIGURE 1 | Scarcity and equity problems in intragenerational resource allocation.

Conventional economists will often use the contingent valuation method (CVM) as a means of performing an environmental assessment. As the application of CVM goes, a set of stakeholders concerned with some set of natural contributions (goods or services from the natural environment including but not limited to extractable primary resources) are asked how much they are willing to pay, in monetary terms, for the preservation of those contributions. It is worth pointing out that in situations of severe resource scarcity stakeholders might better be asked how much of each resource they need for subsistence purposes, or for a decent life. Impoverished individuals may not be able to pay a sufficient quantity of money. As a result, their monetary offering is below the minimum bound of evaluation, as was the situation of individual *F* in **Figure 1**. In contrast, affluent individuals are typically willing to offer relatively exorbitant sums. As a result of this contrast between impoverished and affluent individuals, Costanza et al. (1997) assumed in their well-known CVM exercise that coastlines in wealthy regions should be valued, in monetary terms, at a rate 100× greater than coastlines in poor nations. Such an assumption blinds the economist to situations where distributional issues are central to basic welfare. If concerns over resource distribution are to be taken seriously—as the war on climate change does try to encourage—any approach to welfare that effectively ignores the impoverished fraction, claiming a hypothetical "Kaldor-Hicks improvement" or the like, should be completely avoided.

If irreversible climate change threatens the very viability of the biosphere, as the latest comprehensive IPCC reports suggest (see Section Essential Points of the IPCC Reports), severe resource scarcity must present itself. Serious doubts therefore arise as to whether the moderate scarcity situation considered in conventional economics and assumed in CBA and the SCC approach can apply to the issue of climate change.

Substitution

A, if not the, central issue concerning the mitigation of anthropogenic climate change is whether it is possible to identify, extract and put to economic use primary energy sources without producing harmful quantities of GHG emissions. Effectively, whether it is possible to substitute fossil fuels for less emissive energy source(s). This substitution issue embroils a second perspective on scarcity—a particular resource can be understood as scarce relative to another resource.

Before briefly discussing in a technical manner the plausibility of substitution of fossil fuels by new primary energy source(s), it is imperative to understand substitution as it relates to utility theory. Conventional economists generally assume that money has a quasi-constant marginal utility, meaning the change in usefulness or benefit from the spending of an additional unit of money is relatively constant across scale. According to Georgescu-Roegen (1968) and Marshall (1920) assumed this in his celebrated work *Principles of Economics*. Such an assumption may well seem reasonable if one assumes the social-economic context of Marshall—middle-class life in the late 1800s/early 1900s in a developed, industrialized nation. For someone in Marshall's context, convenience, in contrast to subsistence, was the emphasis. Unlike subsistence spending, convenience spending is indeed flexible. Marginal changes in convenience spending are relatively easy to make, following the increase or decrease of a personal budget. Convenience is a "marginal expenditure" and the substitution of conveniences is understood to be "smooth".

Smooth substitution among goods and associated production factors is both: (1) a cornerstone and theoretical edifice of conventional economics; and (2) essential for the functioning of price mechanisms, conventionally conceived.

But *substitution among production factors is a good deal less smooth than substitution among convenience goods* as production processes are constrained by a set of physical laws—laws constraining the process itself as well as the material inputs of the process. Speaking in general, production factors cannot be easily substituted for each other, as if they were modeling clay. Notwithstanding, in conventional economics, a fluid continuum exists between production and consumer choice. Considering that the substitution of alternative primary energy sources into production processes is anticipated to be a key component of climate change mitigation, it is alarming that the IPCC reports do not consider in a serious manner the actual plausibility of harnessing alternative primary energy sources, needed on a massive scale.

Indeed there is considerable reason to question the feasibility and viability of popularly proposed alternative primary energy source inroads, assumed in a theoretical sense to exist a priori in conventional economics. To illustrate the gravity of the point, a few of the roadblocks confronting modern society are discussed.

The global economy's ubiquitous dependence on fossil fuels for electricity generation is an ironic fact when considered against the lay understanding that electricity is the cleanest form of energy. **Table 1** shows that in 2018 the primary energy source of nearly two-thirds of electricity generated was fossil fuel. Coal, one of the most bothersome sources of GHG emissions, constituted a nearly 40% fraction, with China and India proving particularly reliant (respectively, 67 and 74%). Recent, major gains realized in the USA, from 52 to 29% coal in the mix over the decade from 2008, are temporary changes to the status quo driven by the shale gas boom.

So what about substituting away coal's nearly 40% fraction? And the other main fossil fuels, namely oil and natural gas?

In their operation phase, nuclear power plants do not directly emit a significant amount of GHG, so it is often assumed that nuclear power generation as we know it could be a new type of alternative primary energy source on the global scale. Unfortunately, this is a myth. Considering a world where global electricity demand is met by current or earnestly foreseeable reactor technology, using current global energy consumption levels as a benchmark, proven uranium reserves would last less than a decade. Humanity cannot steer away from disastrous climate change by going down such a path (see the note on a nuclear future in the **Supplementary Material** for a more technical explanation of this point).

After nuclear a typical second suggestion is solar energy, harnessed by photovoltaic (PV) systems or the like. IEA (2021) reports that the global electricity generation by PV systems has reached 3% in 2020. Roughly 95% of the PV

TABLE 1 | Electricity generation in 2008, 2015, and 2018 for eight regions, detailed by primary energy source [compiled from data in ANRE (2011), EDMC (2011, 2018, 2021)].

		Coal	Oil	Natural Gas	Nuclear	Hydro	Bio & Waste	Others
USA	**2008**	52	1.4	18	23	2.3	1.3	2
	2015	34	1	32	19	6	2	5
	2018	28.6	1	34.2	19	6.7	1.8	8.7
UK	**2008**				*n/a*			
	2015	22.9	0.1	29.9	21	1.9	9.9	14.3
	2018	5.3	0.3	39.6	19.7	1.7	12.2	21.2
Germany	**2008**				*n/a*			
	2015	42.6	1	10.1	14.8	3	9.2	19.3
	2018	37.5	0.8	13.2	11.9	2.9	9.1	24.6
France	**2008**	4.4	1.6	4.1	84	4	0.4	1.6
	2015	2	0	4	78	10	1	5
	2018	1.8	1	5.3	71.6	11.4	1.9	7
China	**2008**	89	0.8	0.9	2.3	6.5	0.1	0.1
	2015	70	0	2	3	19	1	4
	2018	66.8	0.2	3.1	4.1	16.7	1.5	7.6
India	**2008**	82	4	6.7	1.7	4.2	0.5	0.5
	2015	83	2	5	3	1	2	4
	2018	73.6	0.5	4.6	2.5	9.5	2.9	6.6
Japan	**2008**	28	12	24	30	3	1	2
	2015	34	10	40	0	8	4	4
	2018	32.3	4.9	36	6.2	7.7	4.2	8.7
World	**2008**	47	6	21	16	6	2	3
	2015	39	4	23	11	16	2	5
	2018	38.2	2.9	23.1	10.2	15.8	2.4	7.4

Data bars and data entries add row-wise to 100% (approximately, due to rounding).

power capacity used to generate that 3% share is still but first generation technology (Fraunhofer ISE, 2018). Second and third generation solar cells have yet to make significant inroads due to a lack of competitiveness of those technologies (Yamada, 2013). The fact that multi-crystalline silicon wafer-based solar cells ("first generation") remain the business-as-usual solution is problematic due, for example, to their high rare earth metal requirements. Even under mid-term rosy technological innovation scenarios, a severe rare earth metal constraint presents itself (see the note on a solar future in the **Supplementary Material** for a more technical explanation of this point). Assuming a very long-term perspective on solar PV futures, at a 2% annual growth rate in global energy consumption (the average from 1980 to 2006), total annual global energy consumption would reach the level of the global solar energy influx in approximately three and a half centuries (fourteen generations). Hence, to be clear, even solar energy is not, strictly speaking, free from absolute scarcity considerations (Glucina and Mayumi, 2010).

What about the again-vogue possibility of achieving a hydrogen economy? Most of the hydrogen demanded in the modern economy is used for ammonia synthesis (50%), with a lesser, still substantial amount used in petroleum refining (35%). Most of the hydrogen demanded (96%) is sourced from hydrocarbon compounds found in fossil fuels, predominantly natural gas, naptha or coal, all preexisting in and extracted from the natural environment. It follows that hydrogen gas in modern society is itself not a primary energy source, indeed it is all but non-existent in Earth's atmosphere. If a hydrogen economy with any reasonable claim of "sustainability" is to be established, an entirely different source of hydrogen must be realized. Despite five decades of interest, such an imaginary, reliant on widescaling processes of water electrolysis, remains distant due to the prerequisite of first decarbonizing the electrical grid, as well as physical difficulties involved with manufacturing a hydrogen grid and a new fleet of futuristic power capacities (see the note on a green hydrogen future in the **Supplementary Material** for a more technical explanation of this point).

In summary, several of the more mainstream alternative energy source proposals were discussed to illustrate the biophysical reality that a substitution of fossil fuels for less polluting primary energy source(s) does appear highly problematic. It is not being claimed that such a substitution is impossible, simply that imaginaries of such a substitution should not be seriously entertained in the absence of involved, critical reflection. Since the substitution of production factors is indeed frequently found to not be smooth, a burden of proof above and beyond "conventional price mechanisms" and "the invisible hand of the market" lies with techno-optimists.

Discounting

It is thirdly instructive to reconsider the meaning of the practice of discounting, which has an important implication for the intergenerational distribution of natural resources in terms of physical amount. The "efficient allocation" of an exhaustible resource is considered, in conventional economics, as follows. Consider for:

(1) a demand function represented by $P_k = u - vQ_k$ where P_k is the price of the resource, Q_k the quantity of the resource demanded in the period k, $u > 0$, $v > 0$, and period k varies from 1 to m;
(2) a marginal cost of extraction represented by E;
(3) a total resource quantity represented by T;
(4) a constraint on the size of T such that $T < \sum_1^m Q_k$, for which $P_k = E$; and
(5) a discount rate represented by d.

The present monetary value of T distributed over m periods is maximized where an equalization of the present values of marginal net benefit (MNB) at the period k is realized. This condition is represented by Equation (1).

$$MNB_k = \frac{P_k - E}{(1+d)^{k-1}} \tag{1}$$

Because $1 + d > 1$, for any k, we then have Equation (2):

$$\frac{P_{k-1} - E}{(1+d)^{k-2}} = \frac{P_k - E}{(1+d)^{k-1}} < \frac{P_k - E}{(1+d)^{k-2}} \tag{2}$$

Following Equations (1) and (2), the inequality $P_{k-1} < P_k$ emerges. This inequality is known in the literature as "Hotelling's rule" (Hotelling, 1931). Hotelling's rule entails that $Q_{k-1} > Q_k$, following $P_k = u - vQ_k$. Hotelling noticed this inconvenient truth of conventional economic analysis, stating that "the true basis of the conservation movement is not in any tendency inherent in competition" (Hotelling, 1931, p. 143). Unfortunately, the $Q_{k-1} > Q_k$ inequality is typically neglected, despite its apparent importance. Hotelling's rule implies that the actual quantity of the exhaustible resource being allocated must decrease over time, in other words $Q_1 > Q_2 > \ldots > Q_m$. Hence, the efficiency criterion in conventional economics, which directs the economist to maximize present monetary value, applying a certain discount rate, places subsequent generations in an ever-worsening biophysical condition.

Consideration of these mathematical models draws into light serious concerns over the ability of conventional economic methods to inform collective decision, such as collective decision over the intergenerational allocation of resources. A hypothetical economic agent, optimizing an objective function for him or herself and given a self-centered set of constraints, can hardly be expected to inform sound decision-making for a collective. And yet CBA, often applied in situations where a collective is at stake, adopts the individual perspective. As Georgescu-Roegen (1977) once put it, future generations require to eat and drink just as emphatically as the present ones. Bromley (1990) similarly argued against the direct use of such individual perspective, bogged down by individual value judgments, when concerned with decision-making for a collective. Efficiency at the individual level has hardly anything to do with efficiency at the collective level. Jevons (1965) himself, a founding father of neoclassical economics, bemoaned the short-sighted nature of individual economic agents and Strotz (1955) anyway revealed that the ultimate behavior of an economic agent is generally inconsistent with an initially derived "optimal" solution. Kirman (1992, p. 117) later contributed a multipronged defense of the thesis that "reduction of the behavior of a group of heterogeneous agents *even if they are all themselves utility maximizers*, is not simply an analytical convenience as often explained, but is both unjustified and leads to conclusions which are usually misleading and often wrong". Really, discounting is only justifiable when evaluating money from an individual perspective and the "social discount rate" is not at all "social" in the sense it is not representative of "society". Further, discounting money has nothing to do with the biophysical foundation of biological life, in particular net primary production in the biosphere.

The privileged position given to money in modern society, a position above transient biophysical goods and services, in fact runs deeper than the conventional economics custom of discounting. Mayumi and Giampietro (2018, p. 152) write on the matter:

> "The first law of thermodynamics dictates that energy cannot be created. On the contrary, money is often created out of nothing and is extinguished into nothing during the recession under the present economic systems, not only by the banking systems, but also by the individual groups of people as well as by the nation states in the form of national bonds. [...] The second law of thermodynamics dictates that energy must decay or dissipate. On the contrary, money is authorized, under the legal and institutional arrangement, to be able to avoid the functional decay while it suffers the structural decay due to the entropy law, so that a positive money interest rate naturally emerges."
>
> Mayumi and Giampietro (2018, p. 152)

The characteristic ability of money to avoid functional decay despite physical, structural decay is itself due to standing legal arrangements. United States law stipulates, for example: "Lawfully held mutilated paper currency of the United States may be submitted for examination in accord with the provisions in this subpart. Such a currency may be redeemed at face value if sufficient remnants of any relevant security feature and clearly more than one-half of the original note remains" (Legal Information Institute, 2017).

In contrast to money, which has the support of such legal arrangements, all other material decays in dutiful accordance with the entropy law. So, a money owner is enabled with the ability to time their economic transactions in a way most advantageous for them. In this way, money interest can be seen to emerge and the quantity of money held by the money owner can be seen to increase according to a set interest rate. Truly it is in this context that discounting is justified in conventional economics. Note again, however, this discounting practice leads to an ignoring of the biophysical basis of the economy—an unfortunate reality where discounting is applied to the intergenerational allocation of natural resources. Mayumi (2020, p. 89) writes on the subject:

> "Money is usually regarded as wealth for an individual. However, money is a debt for the whole community since money entails a promise to pay in term of either existing goods or the production of future goods. Consequently, money puts a community as a whole into long-term biophysical debt. Production entails deficit in terms of entropy (Georgescu-Roegen, 1971) since useful energy and materials are consumed irrevocably, thereby resulting in fewer exhaustible resources."
>
> (Mayumi, 2020, p. 89)

The result of these observations is the so-called "dual nature" characterization of money—money is simultaneously *a form of wealth from the perspective of an individual* and *a debt from the perspective of that individual's embedding collective* (Mayumi, 2020; Renner et al., 2021). Renner et al. (2021) further explain how financial assets such as credit, just as money, express a similar dual nature, a fact which has stood behind major economic booms and busts for well over a century:

> "More than 150 years ago, Macleod [1866/1923, p. 158], a recognized expert on the banking system in the late 1800s, summarized the essence of banking: 'Banks are nothing but Debt Shops, and the Royal Exchange is the great Debt Market of Europe.' Macleod [(1866) 1923, p. 200], further states on the subject: 'If it were asked what discovery has most deeply affected the fortunes of the human race, it might probably be said with truth—*The discovery that a* Debt is a Saleable Commodity.' Macleod's shrewd insights were engendered by his observation of massive acts of commercial bank credit creation in England's post-Industrial Revolution civilization, acts which, together with the *laissez-faire* atmosphere in the late 1800s, enabled a tremendous growth of corporate form."
>
> (Renner et al., 2021)

As it is used in the SCC approach, the maximization of present monetary value assumes, tacitly if not explicitly, the perspective of an individual. This take on monetary evaluation is not conducive to the finding of solutions when faced with a "wicked problem" (Rittel and Webber, 1973), such as climate change. Stiglitz (1997) declares that (conventional) economic analysis is concerned with only "the next 50–60 years". How does he justify the statement of 50–60 years? The power of monetary discounting is remarkable when spelled out. In 50 years, $1 decreases to $0.61 at a 1% discount rate, $0.087 at 5%, and $0.0085 at 10%. In the case of biophysical discounting—discounting in terms of natural resources—the effect of the practice of discounting is incredibly unfair for future generations, especially when considering the rapidly changing nature of our modern world.

SEARCH FOR A "PLAN B" FOR TACKLING CLIMATE CHANGE PROBLEMS IN THE POST-NORMAL SCIENCE ERA

Climate change challenges the traditional role played by scientists. Under the novel circumstances climate change presents, a perspective such as the more humble, post-normal science one of Funtowicz and Ravetz (1990) is crucially important. The aim of science from this perspective is simply to improve the quality of social dialogue, understood as a process, rather not to provide definite, analytical "scientific" solutions—such as a certain SCC value. The reorientation of science toward social dialogue is a dramatic shift, from subservience to science ("follow the analytical guidance generated by scientists") to the establishment of a sort of forum where all concerned persons can debate, even and especially over what the relevant concerns are in the first place. In this way, not only pure economic analysis approaches, a category which includes the CBA and SCC approaches, but traditional scientific approaches in general must seriously reflect on the meaning of social dialogue among involved stakeholders.

A focal point of the post-normal science perspective is problem definition—how to arrive at a proper problem framing through continuous constructive discussions and disagreements, first over the set of relevant concerns and second over the subsequent problem framings. Whereas in "normal science" (Kuhn, 1970) scientific problems are provided to a scientist by the governing scientific paradigm, in post-normal science, being the variety suitable for situations where "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1991, p. 138), problems must be identified and framed in collaboration with an extended peer community. In situations where "facts are uncertain", note that it is often difficult to judge whether values are truly "in dispute" or whether decisions are truly "urgent". Thus, in an effort to move beyond a SCC, the central issue for climate change under the post-normal science paradigm is how to go about managing uncertainty itself—uncertainty in the broadest sense.

In Knight's (1964) well-known text *Risk, Uncertainty and Profit*, particular emphasis was placed on the characteristic forward-looking proclivity of social-economic agents—humans tend to aim to prepare themselves to react to certain situations before those situations actually materialize. Knight (1964) discussed four sources of uncertainty: (1) *perception uncertainty*—we cannot properly perceive the entirety of the situation facing us; (2) *anticipation uncertainty*—we have to infer the future situation from the situation we partially perceive; (3) *effect uncertainty*—we can never know the totality of the future consequences of our own actions; and (4) *implementation uncertainty*—policies cannot be implemented in the actual precise forms in which they are drawn up.

One of the ways these four sources of uncertainty can be at least partially tamed is through the simultaneous entertaining of completely different sets of problem structuring strategy. When dealing with global climate change problems, this translates into the need for transparency, both in the process of problem structuring and in the continuous process of dialogue among stakeholders, scientists, and policymakers. More relevant than a certain SCC, the types of information to be shared must include:

A critical appraisal of the status quo associated with climate change. This critical appraisal is particularly relevant in relation to the selection of a set of important interplays between the anthroposphere and the biosphere, useful for perceiving and understanding climate change issues. Then, to each interplay between the two spheres, alternative interplays with various assumptions must be clearly specified for all concerned people. In this way, it is possible to perceive and share, more or less, the present status of climate change issues and their potential consequences before entering into discussion on policy goals and targets.

(1) A critical appraisal of the process of stakeholder selection associated with goals and targets in relation to climate change. The present IPCC discussion is frequently confined to the identification of GHG emission targets. The SCC approach adds a layer on top—the monetary valuation of GHG emissions. Framed differently, the crucial problem is, first of all, how to select a set of representative stakeholders to discuss a set of goals to mitigate deleterious climate change. Only then is it possible to discuss the nature of the objectives to be shared and to realize inherent disagreements and conflicts among stakeholders. For example, the modern climate change discussion is biased toward a Western, Educated, Industrialized, Rich, and Democratic (WEIRD) societal perspective. WEIRD societies tend to generate persons who are more individualistic and analytical (Henrich et al., 2010), and concerning knock-on effects of that reality can be identified, such as in the SCC approach (i.a., Gayer and Viscusi, 2017).

(2) A critical appraisal of the selection of criteria, with indictors employed as representations of relevant system attributes and performance toward climate change goals. The selection of a set of criteria must reflect the set of shared objectives as they were negotiated by stakeholders in relation to specific goals. After such a selection is made, a set of indicators referring to each criterion are to be discussed and decided on so to properly track improvements and deteriorations, as linked to a particular measurement scheme. Broad domains of such indicators could be economic or political viability, ecological feasibility, social desirability, et cetera. Those indicators must be consistently organized and in a levelized manner, referring to at least three levels—upper, focal, and lower levels within each domain of consideration.

(3) A critical appraisal of the implications of the selection of a particular analytical methodology, where applied to climate change. Out of the many scientific schemes generating criteria and indicators potentially applicable to climate change, we must devise an ingenious combination of various scientific schemes to be adopted by stakeholders in a process of continuous consultation with scientists and policymakers. Single metric approaches, which do often involve along the way a conversion into monetary units, simply fail to capture the requisite complexity of the underlying situation. Understanding each step of procedures used in the set of adopted models is a precursor to being able to adequately share those models between stakeholders, toward a mitigation of climate change. It is important to recognize that none of any of the steps of scientific procedures can escape value judgment, which always does affect, albeit to varying degrees, the final outcome of the modeling exercise.

(4) A critical appraisal of the selection of datasets on which the selected climate change models are applied—we must ascertain whether a suitable set of data sources applicable to the selected models is available. If not, suitable datasets must be created. It is important to recognize an inherent measurement indeterminacy, existing due to the co-existence of a set of equally relevant yet essentially different space-time scales in relation to the phenomena of climate change, leading to a certain indeterminacy in datasets themselves.

(5) A critical appraisal of the selection of a set of system behaviors over time that describes interplays among various parts of those systems and changes within each part of those systems in relation to climate change—the selection of such behaviors over time includes not only the dynamics of various systems but also variables, parameters, and a descriptive domain. Note that "descriptive domain" refers here to the combination of: (6a) a time horizon specification; (6b) a set of analytical durations, inherent to particular system dynamics; and (6c) a set of space dimensions so as to consider relevant interactions among parts of the whole system. Such a selection of a descriptive domain is then reflected in the setting of certain initial and boundary conditions.

These six sets of information must be constructed locally, regionally, and globally. They must undergo continual processes of updating, to improve the quality of the whole dialogue process attempting to tackle climate change problems.

It is indispensable to highlight the *change in the role* of scientists, among them economists, in post-normal science situations such as climate change. Scientists themselves must honestly acknowledge their own ignorance in perceiving and representing the present and future situation of climate change problems. When generating a set of key performance indicators relevant to address some given issue in some given local context, it is often the case that the scientists—experts in their proper domains—know far less than the general, local population. A severe problem in the eyes of one scientist may not even be relevant to the local population, a set of persons each juggling a multitude of concerns. On the other hand, scientists are essential actors in informed deliberations with extended peer communities, insofar as they lend valuable explanations of natural phenomena, inferential knowledge useful for guiding decision-making and shedding light on what the future may hold. The key point here is the need for a perpetual process of transparent dialogue and negotiation between domain experts—often but by no means always scientists—and the rest of society. The post-normal science discourse drives this point home (there of course exist other frameworks, such as the deliberative democracy one, that speak to a similar point). Only then can satisfactory disagreement be reached, a satisficing profile of synergies and antagonisms.

Georgescu-Roegen (1971) himself stressed, to this key point, that "non-scientific" thought always and unavoidably proceeds "scientific" thought, and that scientific thought generated in the past or present need not be valid for the address of future problems. Hence scientists, including economists tempted by the SCC approach, must rather start with humility and avoid at all costs to collapse their explanations and models into rigid sets of static methods, indicators, and monetary valuations. Even if we were to entertain the SCC approach as valid and reasonable, stable consensus on a certain SCC value is no doubt impossible.

CONCLUSION

In this article we have shown that the basic assumptions associated with three concepts adopted by conventional economic analysis (scarcity, substitution, and discounting) are inappropriate when addressing climate change problems. The SCC approach is grounded in conventional economic analysis and so, by deduction, the SCC is not an appropriate approach to addressing climate change problems.

Scarcity in conventional analysis is concerned only with moderate scarcity. A moderate scarcity situation is one in which more than sufficient goods and money, needed to cover the minimal needs of a decent life, are provided. However, if, as the latest comprehensive IPCC reporting suggests, fast approaching climate change threatens the very foundation of net primary production in the biosphere, severe scarcity must occur. Thus, moderate scarcity, the situation envisioned by conventional economics, cannot relate to climate change.

The substitution concept, originally derived from utility theory in relation to consumer choice and adopted by conventional economics, is similarly problematic. Conventional economists accept smooth substitution in production, which is physically constrained. The most important key issue in the climate change debate is whether or not alternative primary energy sources can be identified. We have shown that there are at least four formidable barriers to a smooth transition to primary energy sources that can replace fossil fuels, the modern motive power of Promethean technology. The four barriers related to a high percentage of electricity generated from fossil fuels worldwide—more than 60% in 2018—a dearth of fissile uranium or alternative, more advanced reactor design, a relative insufficiency of rare earth metals for panel fabrication following a hypothetical, massive solar PV rollout, and finally, the fossil fuel origin of hydrogen gas. The typical existence of such technical issues means that smooth substitution cannot be wished upon production factors—the biophysical coherence of production process substitutions must be discussed critically and in depth, not assumed.

Thirdly, as shown in a simple intergenerational allocation of a natural resource example, if the conventional economic efficiency criterion—maximizing the present value of net monetary benefit—is adopted, the physical quantity to be allocated to later generations tends to diminish over time. It diminishes in accordance with the chosen discount rate. A collective decision to be taken concerning the allocation of nature's contributions from an intergenerational perspective challenges the conventional economic approach to problems associated with climate change, which hinge upon future generations. While the efficiency criterion of monetary valuation could be useful for individual economic decisions, as we have shown in Section Critical Appraisal of the Scarcity, Substitution, and Discounting Cornerstones of Conventional Economics, such monetary evaluation is problematic due to money's dual nature. Money, including in the scope of the term a wide span of relatively interchangeable financial assets, is a source of wealth from the perspective of an individual but a debt at the community level. It is the community that agrees to honor the value that money—promises to pay—represents, exchanging for it a certain amount of biophysical goods or services either in the present or as foreseen in the future. The production of these goods or the rendering of these services proceeds in entropic deficit—the thermodynamic reality marching us step by step toward resource exhaustion (Georgescu-Roegen, 1971). The practice of discounting should not be applied to biophysical allocation problems, which are deeply associated with collective decision-making. When considering biophysical allocation, the efficiency criterion is a variety of analytical fallacy from conventional economic analysis, to be discarded.

Ever since the Industrial Revolution, two types of technology have driven a common explosive characteristic, typical of "Promethean technologies": more and more coal and oil extraction, more than what was previously used in the entirety of the economic process. Due to its explosive nature and the related depletion of fossil fuels, Promethean technology has driven humans at full speed into the Malthusian instability trap, leading to climate change problems. Despite a steady string of improvements in the energetic efficiency of technologies, the metabolic profile of society has become increasingly entrenched with fossil fuels. Paradoxically, in spite of efficiency gains, fossil fuel consumption has exploded, a phenomenon known as the Jevons paradox.

Climate change problems demand that we, the collective human society, seriously reconsider our behavior within the anthroposphere and in relation to the biosphere. Net primary production in the biosphere is the vital source of all that humans appropriate for activities in the anthroposphere. Georgescu-Rogen's bioeconomic perspective could be a crucial element for understanding the miscellaneous interplays between the anthroposphere and the biosphere for the survival of the human species. He is the only economist to declare without hesitation that the primary objective of economic activity is self-preservation of the human species (Georgescu-Roegen, 1971). Georgescu-Roegen (1971, p. 277) emphasized the importance of resources provided by the biosphere: "the most elementary fact of economic life, namely, that of all necessaries for life only the purely biological ones are absolutely indispensable for survival". Climate change threatens the human species with devastating degradation and loss in the biosphere. Prior to Georgescu-Roegen's book, a similar concern with long-term survival was voiced by Hardin (1968). As described in his seminal paper in terms of the potential danger of the monetary evaluation method of conventional analysis, Hardin presented two commonplace examples, neither of which has a technical, "optimal" solution. His examples related to problems of pollution and open pasture management. Both these problems are typical decision-making dilemmas, emerging from a set of agents each seeing the world through an individualistic lens. Note that individualistic lenses are often seen to contradict the shared community lens, the latter being primarily concerned with collective, long-term survival. To overcome the dilemmas he elaborated, Hardin proposed laws of temperance based on "socially acceptable coercive" measures. Purposefully or perhaps not, Hardin touched on the essence of the tragedy of the commons *through conventional economic notions* of *gain*, *benefit* and *cost*. For Hardin (1968, pp. 1244–1245, emphasis added), "each herdsman seeks to maximize his *gain*;" "the individual *benefits* from his ability to deny the truth even though society as a whole [...] suffers;" and the rational economic agent has a "share of the *cost* of the wastes he discharges into the commons". Too much greedy concern for money could itself be a powerful cause of the great tragedy of the commons termed "climate change"—it is a concern that instigates lock-in into economic systems that compel the pursuit of self-interest and, potentially but inevitably, draw widescale ruin in the biosphere. The present authors do not have any definite solution to cope with climate change problems. However, the discussion presented in Section Conclusion can contribute to stirring more fruitful investigations among individuals and communities concerned with the climate change issue, being a situation where post-normal science applies.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIAL

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