The ARC-Methodology

A synergetic approach to sustainability

Feasibility study

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Abstract

This feasibility study evaluates the prospect of developing a sustainability assessment methodology for technologies labeled as 'green' or 'sustainable'. We look at the way underlying conceptions of 'efficiency' affect the development and usage of such technologies, suspecting that remnants of ambiguity and incoherence in the foundations of sustainability may have detrimental effects on the evolution of corresponding green technologies.

We theorize that current success criteria evolve green technologies away from ecological sustainability and towards economic profitability, reducing the environmental efficacy of technological solutions and ultimately risking them to cause comparable damage to fossil technologies. We state a need for establishing new sets of success criteria with which to judge the efficiency and effectiveness of green technologies. We outline a possible solution through a concept of co-efficiency between technological and ecological systems, where efficiency is judged by the degree of synergy towards their environmental context.

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1. INTRODUCTION

This study evaluates the prospect of assessing the sustainability of 'green' or 'sustainable' technologies, particularly those constituting renewable energy systems.

The investigation was initiated by questioning what 'sustainable energy' really was and whether it is meaningful to denote some quanta of generated energy as 'sustainable'. Answering this question turned out to require a discussion spanning technology, nature, efficiency, society and economy—often in ways where their philosophical foundations had to be (re)considered. Due to the tendency of philosophical investigations to move towards the abstract and lose practical application, the study is aimed towards a practical outcome: creating a methodology for assessing the sustainability of technologies.

Technologies evolve according to which notion of 'efficiency' they adhere to. Sound evolution of sustainable technologies requires a notion of efficiency that is beneficial for social, environmental and economic factors <u>simultaneously</u>, so that it does not sacrifice one for the other. As we will explain, such a notion must balance the *individual efficiency* of singular factors (a maximization problem) with the *systemic efficiency* of systems as a whole (an optimization problem).

We assume that there exists some optimal configuration between technologies and the ecosystem such that the highest amount of resources are made available for human flourishing. The constraints for social sustainability (on a material level) are thereby given by the technology-environment nexus. For the purpose of making the methodology lead towards some such optimal configuration, a notion of *synergic efficiency* is established which serves as the primary indicator for the methodology.

The validity of the base assumption hinges on whether the world is considered finite or limitless. In a limitless world, maximization will always be the most efficient strategy—it is finitude that makes sustainability an optimization problem. The way a sustainability paradigm (or dimension) considers the issue of finitude is essential for its effect on the ecosystem.

The point of view of the study is a technological-philosophical perspective. However, we do not problematize questions in a typical philosophical format. Instead, we aim at using philosophical overview to chart the caveats and fallacies of current technological development so that notion of synergic efficiency may avoid these culprits. Hopefully, this will address the root cause of why nature loss has become a near-inevitable consequence of technological expansion, resulting in our technological paradigm standing in opposition to the functioning of ecological systems.

We have considered a selection of interdisciplinary literature during the study, most of it published over the 35 years that the modern understanding of sustainability has been in use. We have intentionally drawn from a broad base of disciplines, such as technology, ecology, economy, physics and behavioral and social sciences, to facilitate an innovative approach towards developing an assessment methodology.

The argumentation is structured around how ‘sustainability’ forked into the ‘weak’ and ‘strong’ views in the ’90s (Neumayer, 1999). Views that, from a philosophical perspective, are separated by which success criteria they use for judging ‘efficiency’; whether their choice of indicators reflect economic theory or the natural sciences (Faucheux et al., 1997a; Giddings et al., 2002a; Janeiro & Patel, 2015a) combined with how they consider the finitude of nature.

To investigate if a concept of synergetic efficiency can constitute the foundations of an assessment methodology, we draw from the literature on eco-industrial systems, ecological economy and ecological engineering, fields that already consider synergy an essential factor (Cohen-Rosenthal & Musnikow, 2003; Liu et al., 2019; Odum, 1996; Odum & Odum, 2003; Wang et al., 2020).

The study is funded by the Arctic Centre for Sustainable Energy (ARC) as part of elaborating the question of how to understand ‘sustainability’ within the organization. We also hope to provide grounds for evaluating whether ARC should pursue further research within sustainability assessment theory—a field of research currently regarded critical for steering the green transition in some ‘right’ direction.

We are developing the methodology primarily as an in-house assessment tool for evaluating the complex technological solutions that tend to arise from interdisciplinary collaboration on multi-criteria problems (as typical for ARC projects). However, a secondary objective is to contribute to the ongoing academic efforts of developing an integrated sustainability assessment model with a broader usage field than exclusively green technologies.

1.1 Choosing the right technologies

Philosophers have questioned whether technologies are blessings or curses for millennia. The technology-driven green transition forces us to reconsider these questions, as we are effectively choosing between possible futures through our technology choices today.

But how can we differentiate 'good' technologies from those that are not? And what implementation is likely to realize a *potential* for sustainability that some technology might inhabit? Any technology can, after all, be implemented for 'good' or 'bad'—regardless of how it is construed. And everything else aside: is it even possible to pursue a goal of true ecological sustainability without unacceptable humanitarian costs?

As the questions above demonstrate, a methodology for assessing large-scale technology systems will sooner or later force the discussion into the normative realm. Such considerations are problematic as they transcend the critical divide between «is» and «ought»—between science and politics. Invoking a slippery slope towards value-laden questions, such as: How *should* society be organized? How *should* energy be used? And which *values* should guide the development of technologies? Spite this tremendous challenge, the literature states that "(…) choosing the right technologies is of the utmost importance in order to steer the world along a socially and environmentally sustainable pathway" (Janeiro & Patel, 2015b, p. 444).

Instead of considering this an insurmountable obstacle to providing an answer, we consider it the reason why the foundations for assessing technological sustainability must be developed from a philosophical position, where such questions of value and morality can legitimately be considered. We do, however, attempt to minimize such discussions in this preliminary study, focusing on descriptive aspects of how technologies relate to diverse systems such as environmental systems, markets, monetary systems, production systems and social systems.

1.2 The fundamental technological problem

Most current technologies cannot adapt their functionality to the complexity of environmental systems. Instead, we make technologies efficient by adapting environmental systems to the imperatives of technology, establishing 'normal background conditions' relative to the functioning of technologies. A process that "(…) demands "external" construction and energy in order for [technologies] to be constructed and maintained" (Lie, 2016, p. 156).

We consider it to be the *fundamental problem* of technologies when nature loss becomes a near-inevitable consequence of technological expansion. A meaningful methodology must be capable of addressing this problem. To arrive at such a result, we must start by establishing a clear conception of the challenges at hand, understand how they are interconnected and clarify crucial terms and concepts required for the discussion.

2. Status quo

Conventional industrial activity has already brought several ecosystems to the brink of collapse. The IPBES report considers "changes in land and sea use" and "direct exploitation of organisms" to be more severe environmental threats than those projected by climate change which come in third on their list of environmental concerns (IPBES, 2019a, p. 14).

Non-climatic environmental issues have become more outspoken in recent years, as climate change is in the process of being viewed in a broader ecological perspective (Nemetz, 2022). Much to the merit of projects such as the IPBES report and WWF's Living Planet Report, which establish foundations for assessing the state of biodiversity and habitat so that that the threats can be better compared. The graphic below lists the major drivers for species population decline, as given by the Living Planet Report:

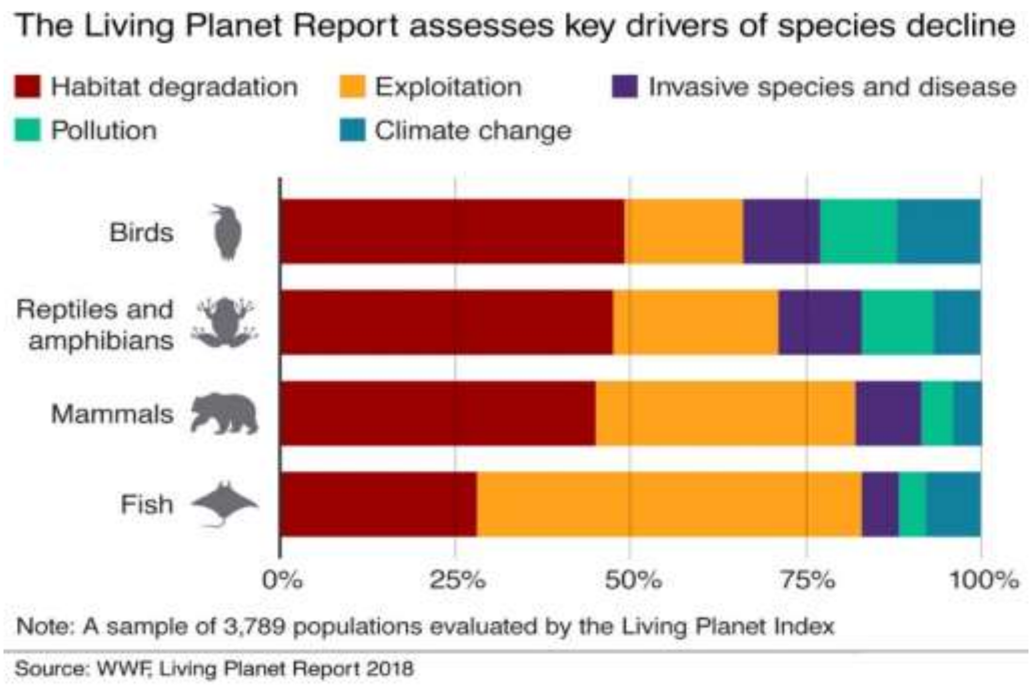

Figure 1: Main drivers for species population reduction

Note how climate change is regarded a relatively small impact factor in this investigation (marked in blue on the far right). Human activity is considered to comprise around 80% of depopulation drivers, while climate change is attributed around 20% of the total threat against biodiversity and species populations (IPBES, 2019b; Maxwell et al., 2016; WWF & Network, 2018). This does not mean that climate change cannot *become* the dominant problem or that we should not tend to this problem *as well*. Rather, it emphasizes the need to see the challenge of climate change in *conjunction* with that of biodiversity and acknowledge that rich biodiversity is a crucial ecosystemic redundancy—no matter the challenge. Ecosystem intactness is not only vital in itself but also the most important mechanism for coping with whatever degree of global warming we are headed for. Unfortunately, here, the statistics are grim.

2.1 The state of biodiversity and habitat

There has been a dramatic decline in global species populations, where over 60% of wild animals have been killed between 1970-2014 (WWF & Network, 2018, p. 90). The most dramatic reduction has been observed in the Caribbean regions having suffered an

89% loss of species population over the same period (Ibid, p. 91). The situation is even worse for freshwater biodiversity, where pollution, forestry practices, disease and climate change as a combined threat has led to a general 83% decline in living organisms. The development is most severe in the Indo-Pacific regions with a 94% decline in freshwater biodiversity (WWF & Network, 2018, p. 95). Overall extinction rates have increased a thousand-fold compared to the prehuman background rate, but even so, the rate of biodiversity loss is expected to escalate towards 2050 (Nemetz, 2022, p. 16).

The monetary cost of restoring ecosystems to some state of “new intactness” (extinct species can never be restored) has been estimated to around $700 billion (Ibid.). Attempts to assess the overall monetary cost of nature loss suggest figures around $4,3 trillion/year in reduced regeneration of renewable resources (Costanza et al., 2014, p. 156). Such estimates cannot be regarded exact but rather seen as methodological baselines for assessing natural capital in monetary value. However, the sheer order of magnitude gives reason to re-evaluate the widespread dogma that development is forced to choose between ecological and economic concerns. Such a dichotomy is functional only so long as we have a surplus of resources to deplete.

When such a surplus exists, those who deplete it the fastest at the lowest costs, will appear to be working at highest economic efficiency, and realize the most profit. However, once the threshold is reached where planetary regeneration of renewable resources no longer satisfies market demands (i.e., for food and materials), any loss of habitat or reduction in regeneration rates will translate directly to inflation—making the causality relation between economy and ecology obvious. We urge to acknowledge this connection before it is demonstrated for us, at least on an academic level.

The issue of nature loss to technological expansion has been widely under-communicated in the environmental debate, as climatic concerns have gotten a disproportionally large share of media attention in recent years. Specifically, *eight times more* over the previous decade (Legagneux et al., 2018, p. 175). This one-tracked focus on climatic concerns has resulted in an unreasonably high acceptance for environmental costs of renewable energy solutions. We are often faced with arguments implying the truism that if only the whole world were run by “green electricity”, then we would have become fully ‘sustainable’. However, renewable energy solutions are generally three times more area-intensive than conventional power plants (van Zalk & Behrens, 2018) so just replacing all conventional energy generation with renewable energy generation represents a massive toll on habitat and biodiversity. Electric machinery can also cut down the Amazonas or turn mountains into alpine resorts, electric trawlers are equally destructive to the seabed as fossil-driven ones and unsustainable mining practices represent the same threat to biodiversity and habitat even if the extracted materials have the secondary effect of reducing emissions.

2.2 Mining

Minerals are the backbone of the green transition, but mining is already one of our most environmentally devastating industries, especially regarding biodiversity and habitat. Mining operations have already negatively affected over 50 million km^2 of land area

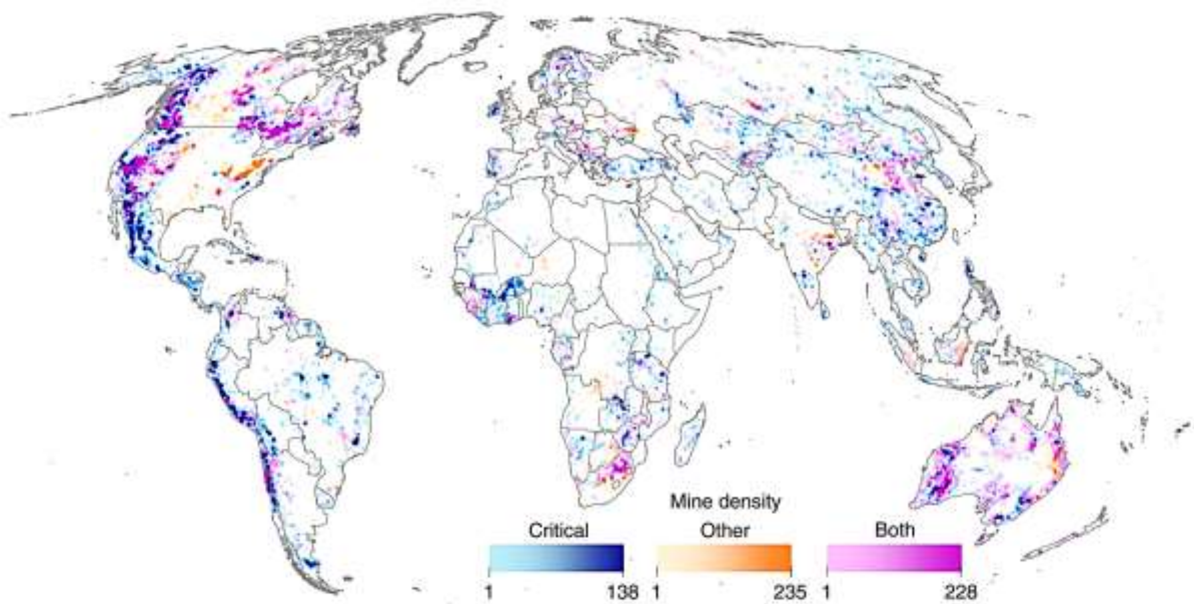

Figure 2: Current ongoing mining operations. Blue represents minerals critical for renewable energy generation, orange represents other minerals, and purple represents both (Sonter et. al, 2020, p. 4)

(Sonter et al., 2020, p. 1) or some 1/3rd of Earth's dry surface. This crude and round-handed estimate does not evaluate the degree of degradation of the affected areas, but the aim of the study is to point out the severe lack of such knowledge within the green transition. The ecological impact of mining is not part of the political deliberation processes on an international level, nor implemented in any policies, which is concerning since 15% of mining operations currently take place in either 'protected' or 'key biodiversity' areas (2020, p. 3).

As an example, 9% of the deforestation in Amazonas is due to mining (Sonter et al., 2015, p. 4) and significant amounts of critical metals come from unregulated mines, where both nature and people are exploited to lower the cost of the green transition to a point where it is economically viable. However, all human activity is considered, only 2.9% of Earth's land area is be regarded faunally intact (Nemetz, 2022, p. 17), posing concerns for a general strategy of sacrificing biodiversity for reduced emissions. The most ambitious targets for sustainable development (understood as emission cuts) require a four-fold increase in metal extraction within 2040[2].

Considering that 82% of mining operations already target minerals that are critical for renewable energy production (Sonter et al., 2020, p. 4) it is unlikely that such a massive expansion of the mining sector can be done neither responsibly nor sustainably—unless the industry is drastically transformed.

Seabed mining could diversify some of the strain. However, the hydrosphere is by many considered an even more strained environmental sphere, as everything ultimately ends up in the sea. Estimates regarding overall sea integrity indicate that only 13% of wildlife can be considered intact (Jones et al., 2018), questioning whether sacrificing aquatic ecological space for the sake of terrestrial sustainability can be regarded a fundamental solution.

There is a huge knowledge gap concerning the seabed, especially regarding the deep seafloor, which limits the accuracy with which it is possible to predict the consequences of seabed mining. Only around 0.0001% of the deep seafloor has been investigated and the little knowledge we have has revealed particularly rich biodiversity (Miller et al., 2019, p. 19). Additionally, many mineral deposits are located around hydrothermal vents, supporting exceptionally rich habitats. Abundance of metals and abundance of life unfortunately seem to correlate underseas as well.

[2] https://www.iea.org/data-and-statistics/charts/total-mineral-demand-for-clean-energy-technologies-by-scenario-2020-compared-to-2040

Understanding deep-sea marine biodiversity is crucial for effective regulation of mining activities (2019, p. 17). One of very few long-term studies having been done was initiated in the Peru Basin in 1989, where a small-scale industrial mining operation for manganese was simulated over an area of 10 km^2. The study aimed to assess the recolonization rates of deep-sea biota after a mining operation. Results showed slow regeneration rates, where plow marks were still visible 27 years later and only a low level of recolonization was observed, suggesting that long-term ecological damage can be expected from deep-sea mining (2019, p. 18).

More recent studies have backed up these preliminary results and made it abundantly clear that seabed mining can cause significant damage and long-lasting effects, and the regulatory frameworks are often outdated or not sufficiently developed to prevent such serious damage (Armstrong, 2022, p. 203). Among several issues, it is unclear which rights and responsibilities different actors bear to the seabed. Most of the seabed (64%) is classified as Area Beyond National Jurisdiction (ABNJ) and governed by treaties drafted before challenges such as mining were an issue. One of the few governing bodies, the International Seabed Authority (ISA), has already issued over thirty licenses for exploration of seabed minerals in this area. An alarming development, considering the lack of knowledge and that the knowledge we already have suggests taking every possible precaution.

To make matters worse, drilling downwards is very challenging when already at large depths. Deep-sea mining operations will generally process large surfaces of shallow depth and are likely to be even more area-intensive than terrestrial mining. Pollutants are also harder to control in the fluid environment, making sea-bed mining potentially even more damaging than land-based operations. Keep in mind that the extracted raw material is utilized for technological solutions that are *also* area intensive.

Oceans are the cornerstones of the Earth's ecosystems, producing over half of the oxygen on Earth and sustaining many species on the lowest levels of the food chain. Additionally, the oceans function as giant mitigation buffers for human activity, diluting pollutants, storing carbon, regulating temperature, breaking down (most) waste products and absorbing/delaying the growing plastic problem. To sustain the levels of mitigation that we have enjoyed until now, oceans must be kept healthy. From this perspective, seabed mining is a risky idea that requires far better understanding of deep-sea ecosystems before being pursued.

Several conservation organizations have called for a complete moratorium on mining and commercial exploration of the deep seabed, emphasizing the need to pause and reconsider whether to continue down this path (2022, p. 204). Technologies represent the primary demand for metals, so researchers, institutions and developers should take clear positions on this issue accordingly and thereby be ahead of the very predictable ecological catastrophe that is likely to follow a poorly regulated rare earth mineral rush in the seabed.

2.3 Causality of climate change: An inconvenient truth

The primary damaging effect of fossil fuels is not their emissions. It is the damage caused by *work* done by *machines* having been *powered* by fossil fuels. Take a second to linger on this thought.

It might seem strange at first, as we are used to thinking of emissions as the unquestionable greater evil. But the primary function of combustion-driven machines is, after all, to do work—not to emit. In fact, great efforts have been made to minimize this accidental by-product of doing work. So, the ratio of work to emissions is *huge*. The truly remarkable part is that the scale of transformation and destruction caused by these machines is so vast, that *even just burning the required fuel* has its own category of catastrophic effects.

The point here is (again) not to question the need to *also* react to climate change, but to do so while keeping in mind the *causality* of work vs. emissions. Climate change is not an independent cause of problems—all emissions destabilizing the carbon cycle are *consequences* of some human activity. Consequently, there is an asymmetric relationship between the environmental- and the climatic problem: If environmental problems are solved in fundamental ways, this will, in most cases, affect the emission problem positively as well (i.e., lowering consumption, moving towards regenerative and low-energy farming, repairing and reusing rather than discarding, etc.). However, solely reducing emissions does not affect any other environmental issues than those having climate change as the *direct* cause. It is hence perfectly possible to *both* revert CO_2 concentrations to pre-industrial levels *and* ruin the ecosystem with electric machines. These are not mutually exclusive outcomes.

It is necessary to have a clear understanding of the interconnections and causality relations within the multifaceted complex of crises comprising the environmental problem to identify real solutions and avoid just transforming old problems into new ones.

At times, the actual reason why we try to avert climate change seems to be forgotten. Somewhat higher temperatures would, after all, be a benign change if no vital systems whatsoever were affected. The actual reason to avoid climate change is the cascade of negative consequences expected to ripple through the ecosystem—due to increased temperatures. This is why the threat severity of different warming scenarios is given in metrics such as biodiversity loss, habitat loss, species reduction and similar ecological indicators.

If we merely exchange *indirect* nature loss (via climate change) with *direct* nature loss (from human activity) and call it "mitigation", then we have lost oversight over the complex of crises that we face—possibly rendering ourselves incapable of identifying fundamental solutions.

Our attempts to mitigate climate change cannot end up costing more natural capital than we preserve, or else the environmental economics of climate mitigation is unsustainable. Sonter et al. issue a warning relative to this scenario regarding the single factor of mining, stating that "[c]areful strategic planning is urgently required to ensure that mining threats to biodiversity caused by renewable energy production do not surpass the threats averted by climate change mitigation" (Sonter et al., 2020, p. 4). This, of course, is a conjecture. We do not sufficiently understand the non-linearity of ecological processes to assess how these two threats will compare hundreds of years from now. However, the case of Sonter et al. is not to speculate on such eventualities; it is to bring forward that such perspectives are ignored systematically in the political discourse and policies of the green transition. In their case, it suffices to show that mining significantly affects the ecosystem to support the claim that these effects must be included in the overall considerations—to take the proper precautions.

Similarly, we urge the academic community to be cautious of promoting naïve attitudes toward electric technologies that downplay their capacity to be equally detrimental to the environment as fossil machines have been. The possibility of causing more harm than good through a green transition is present—and should be taken seriously.

2.4 Renewable, sustainable—or both?

It is crucial to clearly understand what makes something *sustainable* as opposed to *renewable* in the terminology of the green transition. The positive effect of renewable energy is, after all, limited to reducing carbon emissions (*if* the generated energy *de facto* replaces fossil fuels, see section 4.5 for discussion). However, the direct environmental degradation caused by human activity is independent of the energy source, implying that 'renewable' does not necessarily suffice to deem a technology or process 'sustainable'.

If we let renewably generated energy continue the same kind of overexploitation that fossil fuels have facilitated until now, we have failed to address ~80% of our problems, and the green transition might just become yet another ecological disaster. Based only on a different type of fuel**.**

Unless we solve the entire complex of environmental problems with the renewable energy we produce—*can we honestly claim that this energy is, in fact, sustainable?* We might have to require green technologies and green energy generation to be renewable *and* sustainable to expect actual and overall protection of ecological systems from their implementation and operation rather than just shifting burdens around environmental spheres.

3. Efficiency, effectiveness and purpose

Technological efficiency comes down to *how well some means achieve some ends*, and as we will show, the underlying conception of efficiency fundamentally affects the development and evolution of technologies. Before we can reflect further, we need to understand philosophically: what does it mean to be efficient?

To know whether one has been efficient, it is first required to know the *end* we want to achieve. From here, we can develop a technology with some *function* that achieves this end. However, if the end was achieved in a horrendous way, we would not claim the technology to be *efficient*. The qualifier for efficiency is not whether the task was solved—but if it was solved in a *good* way.

Should something be done fast? Or at a low cost? Or with high quality? Or cleanly? Or regenerative? Or beautifully? Or silently? Deciding on some combination of qualifiers for efficiency lies at the core of achieving the intended technological functioning. However, we need to know more than the instrumental aim of the technology to make this choice. We need an idea of its *purpose*. First then it is possible to evaluate which forms of efficiency that are relevant.

At this instant, the technological question becomes a philosophical one. The task of defining a technology's purpose precedes those of technical solution, physical construction and method of implementation—and thus affects all of them.

To proceed in this investigation, we must establish some sort of tentative philosophical purpose for 'green' or 'sustainable' technologies. Unfortunately, such an attempt takes us into the realm of eternal philosophical questions, combining all the worst of the classic ordeals such as *the idea of the good, what is nature, what are humans, what is the meaning of life* and more. We need to take a step back and get out of this philosophical black hole to achieve any progress within this millennium, much less during this study.

We can approach the problem in more practical terms to find an expression that is at least sufficient for this investigation. We are looking for a statement signifying the uniqueness of specifically *green* technologies, differentiating them from ordinary technologies. Further, it is generally believed—or hoped—that green and sustainable technologies can enable us to continue business as usual while simultaneously mitigating environmental problems. One specific formulation would be to let markets produce "high-quality innovative products that can reduce environmental footprint" (Guo et al., 2020, p. 2). From this expectation, we can derive a tentative purpose for green and sustainable technologies, operational for our investigation:

A signifying purpose of sustainable technologies:

To establish a technological layer between human activity and the ecological system, so that humans can live valuable lives without triggering shifts to new ecological equilibria of such magnitude that the conditions for life are altered faster than humans and non-human nature can adapt.

This tentative definition respects the classical anthropocentric purpose of ordinary technologies (making human lives better) without problematizing it, but adds the 'green' requirement of *also* fulfilling some environmental purpose. It circumvents some of the discussion of 'how is nature supposed to function' by denoting ecological sustainability in terms of the coherence between resilience and adaptation. It is philosophically challenging to argue that it is *objectively wrong in itself* to change the climate (by who's authority? Are vulcanos evil then? Why should not the current temperature be the wrong one?). However, if the climate system is tipped into a new state of equilibrium so fast that it causes mass extinction and human suffering, then the harm becomes a problem in itself that is easier to agree upon.

The specifics of 'magnitude' can always be further clarified but for our purposes it suffices that the definition allows for some anthropocentric strain (we are after all part of nature as well) while establishing some basic ecological constraints that are uncontroversial (such as abrupt climate change being considered unfavorable). This avoids the trap of "absurdly strong sustainability" where all human activity is prohibited (Goodland, 1995), while still allowing the claim that some human activity can be wrong from the perspective of sustainability. From this tentative purpose we can inspect *green efficiency* more closely.

3.1 Efficiency in green technologies

Let us quickly recap what we have discussed in this investigation of effectiveness vs. efficiency: Effectiveness comes down to whether a problem has been solved or not, relative to some given purpose. Efficiency, on the other hand, regards *the way* something has been solved, in contrast to achieving the end at any cost.

Let us look at a practical example: Solar panels can generate power for highly efficient LED lighting in a mountain cabin. However, if the lights were driven directly by the solar panel they would only shine as long as there was light outside—defeating the (instrumental) purpose of the technology system (to provide light *while dark*). Such a solution could be highly efficient, and yet, totally ineffective.

A battery could be installed to store power for the dark hours, thereby rendering the technology system effective—relative to its *instrumental* purpose or function. However, if the production of components, its implementation and operation, and the utilization of energy were to cause more environmental damage than the climate mitigation compensated for, then it would not serve the function of protecting ecological systems from human activity—and thus be ineffective as a *green* technology.

The point of this naïve example is to demonstrate the need for defining clear goals for **both efficiency and effectiveness**, relative to some **sum of purposes** if a technology system is to be assessed in a meaningful way that safeguards against 'false' solutions that do not in fact solve problems.

3.2 An existential component of technological effectiveness

Goals for efficiency can be given by an infinite range of indicators. We have mentioned some, such as resource consumption, speed of production, build quality and esthetical concerns. But even more important than which indicators to choose—is the fact that we *do* choose. If goals are not explicitly clarified, they tend to be chosen for us by contextual factors. Kierkegaard describes how a personality ends up in despair by not making active and conscious choices, instead becoming *split in twine* (for-*tvivlet*) between some true self, and the self that is established by external forces, doing the choosing for you. The act of choosing is here regarded A similar existential crisis can be seen in technologies—if their purpose is not consciously upheld by active choice.

For example, liberal economic markets motivate competitors to develop the "best" solution to some demand or problem. As production is initiated, it is not agreed upon what "best" means (*what is the Good?*). Different products and technological solutions then start to compete against each other to capture market shares in the following commodification phase. As people, businesses, societies and governments buy products and invest in solutions, some properties will turn out to be preferred before others. These preferences consequently affect the underlying goals and values behind the next generation of the product or technology. During this process, the conception of "best" is incrementally redefined by the values of the market, establishing new success criteria for what we perceive as 'efficient'.

After a certain minimum of functionality, design and build quality has been achieved, the criteria for efficiency typically gravitate towards economic indicators, so that economic efficiency becomes an increasingly dominant driver for further evolution. This is principally not a problem for ordinary technologies, whose purpose is to increase human well-being, freedom and affluence—disregarding environmental consequences. However, as we have discussed, the situation is qualitatively different for the segment of green or sustainable technologies; they must satisfy *both* human *and* environmental purposes in order to be *effective*.

At this point it is crucial to see that the environmental purpose is in fact the *only* feature differentiating green technologies from ordinary technologies. If the goals for 'green efficiency' gravitate towards increasing human well-being at the lowest cost possible—and within a system that accepts economic externalization as a means for this purpose—then initially truly sustainable technologies will start to devolve. Over time, they will revert to fulfilling human needs as their primary goal, and their distinguishing purpose converges towards doing so only at a *different* environmental expense than the technologies they replaced. For example, sacrificing biodiversity for climate mitigation.

If so, green technologies have become no more effective at their defining purpose than the sunlight-driven lights were for the cabin at night.

It is crucial for a methodology for technological sustainability to avoid the caveat of producing innovative, high-tech solutions that do not in fact solve problems. If both the efficiency and effectiveness of a technology system is assessed, relative to a clearly defined signifying purpose of green technologies, many such situations can be avoided. This would be one of the core tasks of a methodology for technological sustainability.

In addition to identifying and avoiding ineffective types of efficiency, we need to establish an alternative notion of efficiency that fits our purpose. One that embraces the solutions we in fact want. In the following we will investigate whether such a concept of efficiency can be derived from analyzing the **degree of synergy** to arise between **technological and ecological systems**. We are looking for a concept of co-efficiency that is mutually beneficial for anthropocentric and biocentric concerns.

Could such a concept of efficiency maintain the purpose of green technologies, and simultaneously provide ways to maintain social well-being and the functioning of economic systems? In the attempt of answering this question, we need to differentiate between *systemic* efficiency and *individual* efficiency and investigate how these relate to synergy.

3.3 Individual versus systemic efficiency

How can any system be made more efficient? By making its internal parts working better together—which is also the literal meaning of synergy: working together. Synergy can thus be regarded a means for *optimizing* systemic efficiency, as opposed to the more conventional mindset of *maximizing* individual efficiency, achieved by increasing output per device or per process.

Renewable energy systems are generally made more efficient by pushing the limits of engineering, often in regard to scale; continuously constructing bigger dams, taller wind turbines and larger solar plants that require increasingly bigger landscape changes and ever more comprehensive technological support systems for realizing the efficiency of the technology system.

This strategy is not necessarily unreasonable. Especially for wind turbines, where power output increases quadratically with rotor size. Even so, this maximization strategy triggers a cascade of negative consequences for systemic efficiency (negative synergies). For example: (1) Very large turbines require very large roads and machines for construction and maintenance, (2) massive accumulation of energy in remote areas requires transformer stations for stepping up voltages for long-range transport. (3) Very high voltages require gas-insulation (SR-6[3]) of switching gear and (4) a dedicated transportation grid must be built between generation site and distribution grid. Together, these factors make

[3] The most climate-warming gas known, which also provides excellent insulation properties for electrical equipment

out the main crux that (5) one giant wind turbine cannot alone defend such a comprehensive support structure.

To utilize the *external construction* efficiently *many* very large turbines must be built in the same area, thereby motivating systematic over-exploitation of the implementation site, rather than adapting turbine sizes and numbers to minimize ecological impact. This loss of systemic efficiency must be weighed against the increase in individual efficiency, before the most efficient solution can be identified. A synergic approach would decide the size and type of turbines by how the overarching technological-ecological system could be *optimized* rather than how the individual energy output per generator could be *maximized*.

This all sounds very well, but there are still caveats to the synergy-approach since a system can be optimized in many ways. On the most fundamental level, we need to be aware: which relative basis are we optimizing against?

3.4 Synergy… *to what?*

Synergy is already routinely utilized to increase the efficiency of technological and industrial systems. However, they usually emerge within- or amongst technology systems that are already isolated from ecological systems by comprehensive support structures. Synergy is already routinely systematized between technology systems and economic systems or industrial production systems. However, if these systems are not decoupled from environmental degradation, such synergy will directly defeat the purpose of green technologies.

Synergy is not an intrinsically 'good' concept. We can easily optimize the efficiency with which we destroy the environment instead of the efficiency with which we protect it. It is therefore of the utmost importance to be aware *which relative basis* we generate synergy against.

The standardized norms for economic externalization and exploitative practices in current socio-economic systems unfortunately guarantee that we cannot achieve environmental sustainability by generating technological synergy to these bases. Instead, we need to explicitly and consciously choose a basis for synergy that it is capable of realizing the purpose we want green technologies to fulfill.

The obvious choice here is the base of ecology. Unfortunately, such a statement tends to be interpreted as 'sacrificing profit and well-being for environmental concerns', especially by policymakers. However, synergy is by definition a win-win concept. By establishing technological synergy with ecological systems, economic efficiency should increase on several levels: investment costs of implementing the technology would decrease (less comprehensive support systems are needed), increasing regeneration rates at the affected ecological system leads to higher renewable yield, increased CO^2-absorption and increased tolerance for pollutants from human activity. In practice, planetary boundaries would be expanded and allow for more human activity, than would be possible by exploiting synergies that work against the ecological mechanics.

The basic interests of technologies, humans and ecosystems are obviously overlapping and interconnected, for the simple reason that we reside on the same sphere. By considering technology systems and ecosystems as *one* system and taking measures to optimize this supra-system as a whole it should be possible to profit in all sustainability dimensions simultaneously. Such an approach would only prohibit the *maximization* of profit in *any* one dimension, since that would require leeching on resources from the other dimensions.

However, acknowledging this form of systemic profit requires the fruits of systemic effectivization to be recognized. A pragmatic way to establish a quantifiable metric to denote such overall and mutually beneficial optimization could be to simply classify and count the ongoing synergy effects in a technological-ecological system. Increased internal efficiency of this system will always correlate either to an increase in the *number* of synergy effects, or the *magnitude* of some specific synergy effect. Meaning that the efficiency of a system can be increased by increasing its complexity—or by creating support structures that increase the magnitude of a few synergy effects. Which we claim to lead to the fundamental technological problem, Higher complexity leads to additional synergy effects being manifested, which leads to further negative entropy and increased enthalpy (sum of internal energy) of the system, freeing up useful work energy (Jaffe & Febres, 2016a, p. 1). Thereby making the system overall more thermodynamically efficient. We call this strategy *complex integration* of technologies (appendix 3).

An example of a complex integration scheme would be to install smaller wind turbines near- or on the locations where the power is needed in combination with solar panels for compensating load, using grid-controlled appliances to regulate voltage and frequency (much as in the ARC-project Smart Senja). This contrasts the centralized strategy of large wind parks supplying power to a power grid spanning several countries or large parts of a continent, which is regulated by economic markets rather than local needs.

The smaller turbines would generate less power per device (less individual efficiency) but would require minimal support structures. No roads, transportation lines or transformer stations would need to be built (increasing systemic efficiency). They require less specialized tools and equipment for installation, operation and maintenance and would allow local entrepreneurs to construct and manage the installations, stimulating local economies (socially and societally efficient).

It remains to chart exactly how much loss of individual efficiency that can be regained by increased systemic efficiency. Further work on the ARC Methodology could answer such questions and suggest ways to find an optimal balance between systemic and individual efficiency for different technology systems. Before we propose how such an assessment in further detail, we need to cover a bit more ground. It is necessary to understand how the global market influences we perceive efficiency, before we can correctly judge large-scale efficiency of green technologies.

3.5 Market-derived success-criteria

The ‘global market’ is currently in the process of specializing towards mass production of renewable energy technologies. Standard approaches for increasing market efficiency revolve around lowering financial and production costs by means such as cheap labor, low cost of capital, learning effects and economies of scale (Apostoleris et al., 2021, p. 646). After a technology has matured, these financial and social improvements can affect the resulting Levelized Cost of Energy (LCoE) more than improvements in the technologies themselves (see fig. 3).

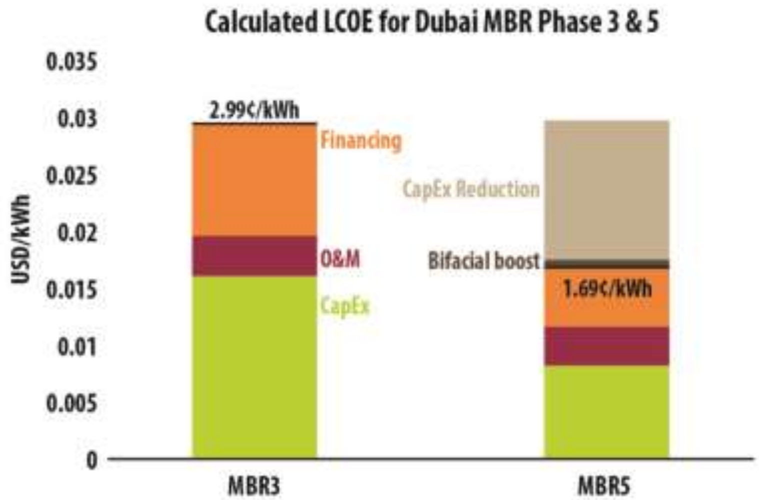

Figure 3: The difference in LCoE between two solar plants in Dubai. We see how only a modest reduction in price is attributed to technological advance (using bifacial solar panels), while 90% of the reduction is due to reduction in capital expenditure (CapEx). (Apostoleris et al., 2021, p. 646)

To produce green technologies at a scale capable of inducing global change, it is hugely advantageous if they are attractive for industrial mass production systems. It can therefore feel intuitively logical to include economic indicators as guiding principles for their development—even at early stages of research and development. University departments often select projects and funding strategies towards the requirements for external financing such as partnerships with local businesses and/or multi-national companies.

As a technology proceeds from development to deployment, such considerations also affect implementation strategies. However, as we shall see, the power of the market does not come without a price.

3.6 Ecological modernization

Approaches that use market mechanisms as means for steering technological development towards mitigating environmental problems fall under the concept of *ecological modernization* (Lamaud, 2013, sec. 1.1). Very briefly described, it can be seen as “(..) a system of beliefs and values attached to a project of environmental restructuring of modern societies” (Ibid., p. 85). It is a moderate position between denial of crisis and a radical ecology, compatible with current political, economic, social and technological views.

Ecological modernization suggests that a form of ‘ecological rationality’ emerges from technological development and market-based instruments, which is anchored in modernist beliefs and a positivist epistemology (Ibid.). However, philosophers have expressed concerns about this approach for decades, issuing warnings of pernicious caveats associated with these beliefs—perhaps most prominently by the technology philosopher Jacques Ellul. He stated that “[t]he great mechanism of production is self-augmentation, which is in reality the emergence of problems, dangers and difficulties”, implying that market-driven development (one sort of self-augmentation) tends to create new problems instead of solving the existing ones in fundamental ways. The tendency is triggered when the *goals* of the technologies are not being consciously chosen and instead emerge from the production process itself, so that “[t]echnique [read: technology] does not develop according to specific ends to pursue, but according to already existing possibilities of growth”.

Today, self-augmentation and growth for the sake of more growth is no longer seen as a cause for concern. Instead, these motives have become standardized drivers for technological evolution. Governments and even universities intentionally adapt systems and selection processes towards generating synergy with production systems and economic systems. Consequently, technological solutions that support and augment the growth of such systems are perceived more attractive for further development. This can, technically speaking, be considered acceptable for ordinary technologies, but it causes green technologies to devolve away from their original purpose (mitigation of environmental problems) towards becoming competitive in the market by means of their very own sets of economic externalities.

3.7 Back to market-derived success-criteria

When the LCoE of a renewable energy technology gets below that of a fossil fuel, it automatically becomes attractive to the market. Ecological modernization theorizes that this attractiveness will push the market towards sustainable development by outcompeting the 'bad' alternatives. However, the inverse mechanism is actuated at the same time: environmental and social compromises are made to lower the price of the technology. For example, accepting environmentally unsustainable mining practices, exploitation of workers in developing countries or the sacrifice of biodiversity and habitat to lower costs of renewable energy installations. Green technologies can thereby start out with clearly defined goals of environmental mitigation, but through feedback mechanisms with production- and financial systems their ends are incrementally modified. Changing the original purpose of environmental mitigation towards increasing economic growth—by externalizing costs onto non-atmospheric environmental spheres. When enough compromises have been made, the LCoE's of renewable energy will in fact be comparable with those of fossil fuels (where costs are already heavily externalized). But only due to a *different* environmental and social price.

Such results resonate with the Ellulian critique of ideologies falling in line with ecological modernization: by failing to question technological progress they allow development to become driven by opportunity for growth (a contextual factor) rather than the original intention of the technology (failure to choose actively and consciously). Changing the function of innovative green solutions from mitigation—to consumption. A tendency that opens for green technologies eventually being put in opposition with a philosophy of ecology (Lamaud, 2013, p. 94) as the prospect of consuming our way out of a consumption crisis is unrealistic (Grant, 2011; Huesemann, 2003; Huesemann & Huesemann, 2008).

A similar rationale lies behind our claim that a methodology of technological sustainability must primarily solve the 'fundamental technological problem' (nature loss to technological expansion) before technology-induced problems can be solved by means of even more technology. Attempts at more shallow technological solutions tend to only shift burdens around environmental spheres, rather than solving problems in fundamental ways—leaving the world in technological despair.

Kierkegaard's solution to being in despair was to start making active and conscious choices. He considered any active choice as a way of *choosing one's self* (Kierkegaard, 1843, pp. 203–205), and thereby maintaining one's identity by establishing cohesive personality lines over time, consolidating one's personality (1843, p. 164). Similar existential perspectives emerge for the identity of technologies in the struggle of maintaining their signifying purpose in a commodification process. To steer how they evolve when drawn between market efficiency and environmental functionality, it is necessary to actively and consciously choose which success-criteria their efficiency is judged by and ensure that these choices are not being made *for us* by markets, productions systems or other contextual factors.

This existential component of efficiency assessment makes our methodology philosophically robust to the Ellulian line of critique and increases the extent to which ideologies such as ecological modernization can be part of a solution. It is important to note that these perspectives are not about being technophobic or luddite in the approach to modernization or denying development. It is about having an attitude of questioning the implications of technology-related choices as rigorously and systematically as we do with engineering choices when solving technical problems (Lamaud, 2013). **Considering that most of today's problems—from consumerism to overpopulation—are consequences of technological innovation, we need to proceed very carefully and maintain a profoundly humble attitude to technological development, if we are to succeed in solving our technology-induced problems by implementing even more technologies.**

3.8 Economic theory and market efficiency

For the reasons discussed, we believe that it is not optimal to have market considerations deeply embedded in the development and deployment of 'savior' technologies. When the efficiency principles of economic theory are combined with (current) market mechanisms, they seem to evolve any technology—green or not—towards increasing consumption instead of mitigating environmental problems (in line with the fundamental critique presented by Ellul over fifty years ago). These perspectives throw us back to the recurring theme of efficiency versus effectiveness. This time with emphasis on the *type* of efficiency we cultivate.

The liberal market does an excellent job of increasing *economic* efficiency, by lowering costs of production and maximizing profitability. However, the distinguishing feature of green technologies is not their profitability, but whether they are *environmentally effective*. The goal of generating profit is a *different* objective being assigned to green technologies in the phase of meeting market requirements for successful commodification, and as long as economic externalization is an accepted means for increasing efficiency of this (new) purpose, it will work against their signifying purpose. As an example, consider the effectivization of farming in the US:

Before 1940 farming was generally ‘green’ by current standards. It took 0,4 calories of energy to produce one calory of food (Manning, 2005) and most foods were sold locally and unprocessed. In 2002, however, three calories were spent for every calory of food grown (Norton, 2010, p. 1). When factoring in modern norms for distribution and processing, an estimated 7-15 calories of energy is spent per calory of food served at a US household table (Hendrickson, 1994; Norton, 2010, p. 2).

So, farming in the US has gotten **ten times** less energy efficient on a production level since WWII. And when new norms for transportation and post-production are factored in, we are looking at a **30-fold decrease** in energy efficiency of the entire food production system. Still, this development is called an “effectivization of agriculture”. How can this be…?!

In this example, “efficiency” refers to increasing the *production capacity* through *energy-intensive technologies* (such as chemical fertilizer and pesticides as well as bigger and faster machines). This allows fewer laborers to generate more capital, freeing up labor capacity that can be used to push the production possibilities curve (PPC) outward, which satisfies the neoclassical economic conception of efficiency (Huesemann & Huesemann, 2008, p. 797). This growth-based success-criterion has taken modern farming from green to black through the alibi of effectivization and the fact that it is rational for growth economies to sacrifice *energy* efficiency for *time* efficiency, in pursuit of the overarching goal of economic growth. A function of time.

This example demonstrates the need to be conscious of- and critical to *which kind* of efficiency we refer to when evaluating an effectivization. It is a systemic and contextual issue to translate green efficiency into economic profit, and much of the problem we seek to address with our methodology is caused by industrial systems reaping economic advantages of rather limited forms of technological efficiency—but still realizing profit by distributing negative externalities onto nature and the commons.

The current generation of green technologies tends to be effective relative to climatic concerns, but sacrifices biodiversity and habitat to gain the economic edge needed to compete with a heavily subsidized and externalized fossil fuel industry. But if "green" technologies are rendered ecologically unsustainable (for non-atmospheric spheres), their purpose is severely defeated. Green technologies are effective if—and only if—they mitigate environmental problems over *all environmental spheres* while *also* solving technical problems. Or else, we might need a new color technology for those that are climate-specific.

A sustainability assessment of green technologies must be independent of such bias toward economic efficiency. Although the practical world might have to defer to some degree of compromise for some time to come, the academic realm should actively and consciously choose to maintain the purpose of green technologies by judging technological sustainability from a sound philosophical basis, to avoid technological despair. A crucial prerequisite for a methodology to contribute to this aim, is to establish a coherent and operational concept of sustainability.

4. A COHERENT CONCEPT OF SUSTAINABILITY

The modern concept of sustainable development was coined in the *World Commission of Environment and Development* (WCED) report: *Our Common Future* (1987). Many considered it an attempt to resolve the tension between economic growth and environmental concerns that followed the *Limits to Growth* report (1972). However, *Our Common Future* did not mainly address environmental problems. Rather, it considered the practical aspects of coping with the predicted population growth and the consequent increase in demand for food and commodities. This was seen from a socio-economical perspective, with the primary goal of leveling the increasing economic and material differences between the global north and south (Meadowcroft et al., 2019, pp. 295–311). However, it was implicitly assumed and accepted that the effort for social sustainability would negatively affect the environment. This in mind, let us reiterate the well-known definition of sustainable development:

> (…) meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987)

…which has been debated ever since.

Even though *Our Common Future* did tackle the concerns of population growth, it did not address the issue of economic growth in itself—which was a significant part of the critique of *Limits to Growth*. Instead, the WCED-report focused on mitigating global economic differences from a justice-centered point of view. Considering economic growth as a tool for achieving socio-economic sustainability. The foreword of the report bluntly states that "[w]hat is needed now is a new era of economic growth—growth that is forceful and at the same time socially and environmentally sustainable" (WCED, 1987, p. 7).

It was speculated that this combination of goals could be achieved if industrialized nations shifted towards less material- and energy-intensive activities (WCED, 1987, p. 47). A practice coined as *eco-efficiency* by the *World Business Council for Sustainable Development* (WBCSD) in their publication *Changing Course* (Schmidheiny, 1992). It was thereby acknowledged that ecological limits did exist, but it was also claimed that these could be avoided by adhering to this new notion of efficiency. The soundness of this rationale was not subjected to philosophical scrutiny before becoming a fundamental principle for global policymaking. Philosophers were, however, quick to point out several critical problems, such as:

- What are '*needs*'? And who should define them?
- How can we predict those that future generations will have?
- How long of a timeframe is "*generations*", exactly?
- How do commercial markets affect 'needs'?
- How should the different dimensions be weighted?
- and (as relevant for us), by what methodology?

These issues and many more have been thoroughly debated in the philosophical discourse, i.e., Michael Redclift (2005, p. 213), Lyle Grant (Grant, 2011) or Naomi Klein (1999, 2002, 2004 and more), but they did not transcend to a political level[4]. Consequently, the UN's formulation of the *Sustainable Development Goals* (2015) inherited many of the issues and unclarities of the original definition. Consequently, they have been criticized for problems such as "(…) being inconsistent, difficult to quantify, implement and monitor". Particularly regarding "(…) socio-economic development and the environmental sustainability goals" (Walid & Luetz, 2018, p. 341). Analysis of the maturity of the 17 main goals and the 169 sub-goals concluded that "Out of 169 targets, 49 (29 %) are considered well developed, 91 targets (54 %) could be strengthened by being more specific, and 29 (17 %) require significant work." (Brigitte Baptiste, 2015, p. 6).

Considering the outlook for technological development within 2030, it seems highly unrealistic to expect this development alone to both reduce poverty and increase economic growth, while simultaneously emitting less and also conserving more natural habitat and biodiversity. Such views of 'technological salvation' were more realistic in the '90s and early 2000s, when there was *time* to expect unexpected solutions. Today, we know with a high degree of confidence what kind of technological advances we can expect to have implemented over the next decade, and neither wind turbines nor solar panels can achieve sustainability in all these areas simultaneously simply by reducing emissions. As we have argued, many of the problems we need to solve are interlinked on deeper levels, and several of them in such a way that the solution to one problem will aggravate another.

These dilemmas make the discourse around sustainability to frequently state the need to ''integrate'', ''balance'', and ''reconcile'' the pillars of sustainability. Unfortunately, "without necessarily articulating what this means in practice" (Purvis et al., 2019, p. 690). Critical questions addressing such uncomfortable trade-offs tend to be answered in ways that "appear to depend on the level of optimism [that] the work in question is pitching for" (Ibid.). We are clearly in need of a more realistic approach to problem-solving, one that transcends that of naïve technology optimism, tackling the philosophical problems residing in the foundations of sustainability.

[4] The work of Nussbaums 'Capability approach' is currently being considered for political inclusion by the UN, however, this is a very recent development.

4.1 Unsolved philosophical challenges

Problems on the deeper levels due to sustainability implicitly combining philosophical dualisms that have not been bridged in generations. For example, the pillars of sustainability are reducible to anthropocentric and biocentric positions, which are considered philosophically incommensurable and have escaped unification for centuries. The classical definition of sustainability combines holistic and reductionist concepts, and its interpretation also depends on ongoing philosophical debates, such as that of how we should relate to future generations. Problems such as these have been pointed out as significant obstacles to a coherent and operational concept of sustainability (Purvis et al., 2019, p. 682).

A similar philosophical problem, affecting technology development on a global scale, arises from the liberal principle of avoiding conceptions of 'the Good' in political decision-making. However, an inconsistency arises considering that the basic purpose of technology is exactly to achieve some(one's) conception of something Good. And the technology that achieves this Good, better than another ("better" by *yet* another conception of something Good) is considered *more efficient.* So, implicitly, we *do* take stances on many such normative and value-laden questions that we seek to avoid—just not rationally and consciously! Instead, it 'happens' through the practical processes of developing, implementing and commodifying technologies.

This way, values and world views become baked into the physical construction and design of technologies, whether we intend to or not. Requiring engineers, politicians and economists to be aware of how their practical work translates to applied philosophy over advanced and highly controversial issues. If they are not, the assimilation of values into the form and function of new technologies is subjected to a somewhat random selection process, often guided by the fall-back solution of evaluating cost-efficiency instead of ecological efficiency, invoking the fallacies of market-driven development that we discussed (section 3.6).

An attempt to circumvent these problems emerged from the sustainability discourse by dividing sustainability into the well-known pillars or dimensions and treat them as if they were separate and distinct bases for evaluation. Unfortunately, in reality they are not. And void of some shared ontology for how the term relates to physical reality, different schools of thought interpret and weigh these pillars very differently (Purvis et al., 2019, p. 681) leaving the internal structure of the term unclarified, making it ontologically open (2019, p. 692) and vulnerable to differing underlying conceptions of efficiency, effectiveness and purpose (for example, those held by an engineer, a researcher or the CEO of a company rather than the ecologist conception).

These underlying views and values break the concept into different paradigms that affect the technology development on several levels by influencing "(…) the choice of indicators, the allocation of priorities/weights/hierarchies as well as the rationale to make decisions" (Janeiro & Patel, 2015b, p. 445). Due to the incommensurability of these differing paradigms, communication tends to break down between them when abstract theory meets physical practice since there is no consensus for an epistemology of sustainability. For example, the bulk of ecologists tend to consider the prospect of eternal growth unsustainable, while the majority of politicians believe in economic growth as a feasible strategy towards sustainable development (resulting in economic growth being included in the current SDG's). To reconcile such differences, we must identify where the incommensurability lies in the philosophical fundament.

4.2 Paradigms of sustainability

The classical interpretation of sustainable development divides the concept into **social**, **environmental** and **economic** pillars, considering them to be distinct and separate, although, overlapping. It is a common intuition that if all three dimensions are considered and weighed against each other on equal terms, the result would be a balanced decision leading towards sustainability. However, this intuition masks a voting-technical flaw.

Both the economic and social dimensions are reducible to anthropocentric positions, while the environmental dimension is the only biocentric position. So, in any 'fair' weighting 'on equal terms' the concept of sustainable development is biased 2:1 against ecological concerns. Additionally, economic arguments tend to carry more weight than ecological arguments when economic growth is considered a functional and even preferred strategy towards sustainability, biasing sustainable development even more against ecological considerations.

To make the concept operational for methodological purposes, we need to find ways to omit such ambiguity to concretize a coherent interior structure of the term. Purvis et al. state that "any rigorous operationalisation [of the sustainability term] requires explicit description of how it is understood" (2019, p. 692). To arrive at a philosophically sound interior structure, operational for methodological purposes, we bring forth some observations:

1. If economic trade were to be removed from the world, the ecosystems would not collapse. Ecosystems are not dependent on trade.
2. If all humans disappeared, natural systems would still exist and function. Nature is not dependent on the social dimension.
3. It would, however, be very hard for humans to exist in the absence of an environment. We would not be able to sustain our lives or evolve into humans in the first place, unless environmental systems had supported the evolution of our primordial RNA. There would also be very little of value to trade.

We therefore regard it ontologically uncontroversial to claim that the economic dimension is a subset of the social dimension, which is a subset of the environmental dimension. Such an interior structure of the sustainability term has been formalized in the literature, for example by Giddings et al. (2002b). They attempted to update the internal structure of the term by a more detailed analysis of its ontology, than we have crudely illustrated.

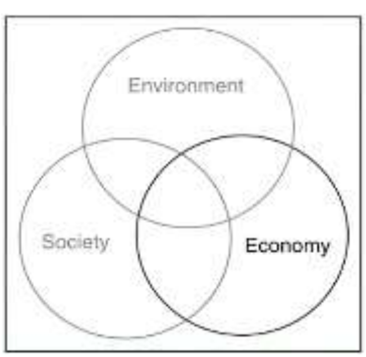

Figure 5: Common three-ring sector view of sustainable development Giddings et al., 2002, p. 189)

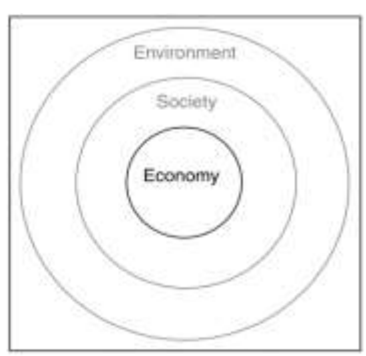

Figure 5: Nested sustainable development–view (Ibid., p. 192)

Gidding's conceptualization builds on the notions of *weak* and *strong* sustainability introduced in by Solow and Hartwick in the '70s, re-actualized in the '90s (Faucheux et al., 1997b; Goodland, 1995; Neumayer, 1999). Similar views have been developed through other disciplines, such as "the triple bottom line" within the field of sustainable business (Elkington, 1994).

As a common denominator, these conceptualizations require economic and social activity to be regarded within an environmental frame and prohibit economic and social criteria from becoming *primary* indicators for sustainability. Such an interior structure distances the term from the constructivist world views of social systems, aligning the ontology of sustainability with the natural sciences, such as physics and ecology.

The social sciences, however, are not necessarily prone to accepting such an ontology. "Reality" is considered what every consciousness makes out of its collections of impressions, having been received from some external world that might—or might not—be there. A world view that puts human *perception* at the centre of the physical universe, making 'the mind' the primary category, in line with the Kantean dogma. Elevating the human mind above the physical, rendering the external world inferior to human capabilities and making technologies extensions of this epic battle of rationality and morals against the primitive forces of nature. Protecting us from them and nurturing belief in economy and other social phenomena to be considered equal—or even superior—to ecology. Requiring ecological questions to be regarded within a socio-economic epistemology rather than the empirical science of ecology. This clash between physics and constructivism is what we believe to be the fundamental schism of sustainability.

4.3 The philosophies of weak and strong sustainability

The terminology of weak and strong sustainability arose from work on Environmental Economics in the '70s, theorizing that 'human capital' could substitute 'natural capital'. The idea of strong sustainability, on the other hand, is rooted in the natural sciences where sustainability is understood as the *preservation* of natural value. This line of thought considers socio-economic structures to be *limited* by a finite environment and a certain economic development can be considered sustainable if the activity allows the natural environment to sustain over some (undefined) span of future generations.

On the other hand, the weak conception is rooted in the traditional neoclassical concept of *capital and utility*. Success is measured by aggregated income, and the value of the natural environment is translated into economic terms. Here, a certain economic development is regarded sustainable if future generations can sustain a similar degree of *aggregated income*, measured in GDP, GWP or some other economic measuring stick (Faucheux et al., 1997b; Janeiro & Patel, 2015b; Neumayer, 1999).

The critical difference between these views is that the weak conception "(…) assumes substitutability between human-made capital and natural capital, as long as the aggregated income does not decrease over time" (Janeiro & Patel, 2015c, p. 440), while the strong conception considers natural value to be irreplaceable. The key to claiming environmental sustainability from a weak position is belief in that (…) human ingenuity and progress in science and technology will solve all current problems" (Huesemann & Huesemann, 2008, p. 789)—not too different from the hubris ascribed to the human mind by the classical philosophical tradition.

However, despite the 30-odd years of practicing a weak conception of sustainability, there is little empirical evidence supporting a technology optimist salvation view. Loss of biodiversity and increasing emissions[5] are still coupled with economic growth (Otero et al., 2020, Chapter 2). Processes and technologies have become more energy-efficient and also been attempted decoupled from resource use, but the efforts have not yielded any absolute reduction in emissions or biodiversity loss. On the contrary:

> (…) there is ample evidence that sustained absolute decoupling has not occurred so far (Alexander et al., 2015; Cspereklyei & Stern, 2015; Krausmann et al., 2013; Steinberger, Krausmann, Getzner, Schandl, &West, 2013; Ward et al., 2016; Wiedmann et al., 2015;(…). These studies suggest that, under current socioecological conditions, economies with higher GDP tend to (i) consume

[5] When embodied emissions are factored in, see section 4.6 for discussion

more raw materials and energy, (ii) occupy more productive land, and/or (iii) use it more intensively.

(Otero et al., 2020, p. 4)

These perspectives are further substantiated by updated simulations of the *Limits to Growth* scenarios, showing that its predictions remain remarkably accurate and claiming that "(…) there does not appear to be other economy-environment models that have demonstrated such comprehensive and long-term data agreement" (Turner, 2014, sec. 8).

Note that throughout the rest of the study, we will use the concepts of weak and strong sustainability as a continuum where the weak/strong division is considered extreme positions defining a spectrum of sustainability perspectives (Janeiro & Patel, 2015b, p. 441). More realistically, weak sustainability implies little or less concern for biological diversity and nature conservation, while strong sustainability considers biological diversity and nature conservation as essential prerequisites for socio-economic development. To solve this incommensurability, we need to find some common epistemology that both factions can agree with.

4.4 Ecology. A value system—or a science?

It would seem intuitive to manage the workings of natural systems by the sciences of how natural systems work. However, the science of ecology has acquired a strange position of academic and political vacuum over the course of the green transition. Recommendations from this evidence-based science of natural systems are often considered inferior to economic recommendations—even for questions regarding the stewardship of natural resources. Instead, social metrics of supply and demand are considered equally or, at times, even more relevant. This turns the tables on sustainability from strong to weak when ecological issues are assessed within a social and economic frame rather than by a relevant field of science.

Arguments that challenge the flaws of such a sustainability ontology are always countered with some form of technology optimism, combined with a humanitarian argument; Faith is proclaimed in technological capacities yet to come—if only social and economic systems are allowed to thrive. Then, this belief is combined with the 'realism'-

argument, that reduced economic growth will cause unacceptable humanitarian and societal consequences. Implying that environmental salvation in fact depends on sustaining economic growth, inferring the corollary that poor people in developing countries are the real threat to the environment due to inefficient practices and inferior technologies. Often accompanied by the claim that if only developing nations "got up" to our level of industrialization, then the environmental problem would solve itself. Therefore, the process of industrializing must continue, and we should have faith that the market is eventually going to come up with solutions that no one could have imagined.

The absurdity of this claim is easily spotted when considering actual consumption of industrialized vs. developing countries. Our current resource consumption requires the equivalent of 1.8 earths per year, which is problematic in itself, but we would need 5.1 Earths if everyone were to live as people in the US. However, less than half an Earth would suffice if everyone lived like people in Yemen, Haiti, Afghanistan or Ethiopia[6]. Empirical data simply does not support the growth/industrialization-theory towards sustainability, as no developed nations currently stay within their biocapacity while most developing nations still do.[7] Concerning the question of realism, it seems far less feasible to solve a problem of overexploitation by tripling resource- and energy consumption, than by confronting such wishful thinking.

This line of argumentation is, however, compelling to policymakers. It opens for promoting increased consumption as a strategy toward environmental sustainability, making it appear rational to guide the management of natural resources by economic theory instead of ecological science. Producing the estranged position of ecology in the green transition and establishing political precedence for market-driven weak sustainability over knowledge-based strong sustainability.

To be fair, it should be noted that there are studies advocating a theoretical possibility of staying within specifically *climate* targets through substantial technological efforts, giving merit to some aspects of the technological salvation thesis. However, fact is that these technological solutions and their production systems are not yet decoupled

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[6] https://www.overshootday.org/how-many-earths-or-countries-do-we-need/
[7] https://data.footprintnetwork.org/#/

from non-climatic types of environmental degradation, which we have argued to be at least as significant a threat to Earth systems as global warming (at current trajectories, see section 2.1). Seen from a technology-philosophical angle, there are simply too many economic and social *rebound mechanisms* working against solutions that mitigate problems across all environmental spheres. Huesemann&Huesemann (2008) have investigated some such rebound mechanisms within the framework of neoclassical growth theory (2008, sec. 3.3), we will describe one of these in the next section.

4.5 One rebound effect of sustainable development

Market mechanisms can potentially neutralize the environmental gain of increased technological efficiency. Below is a graph of global primary energy consumption since 1970 where we marked the start of sustainable development, in 1987 (fig. 6):

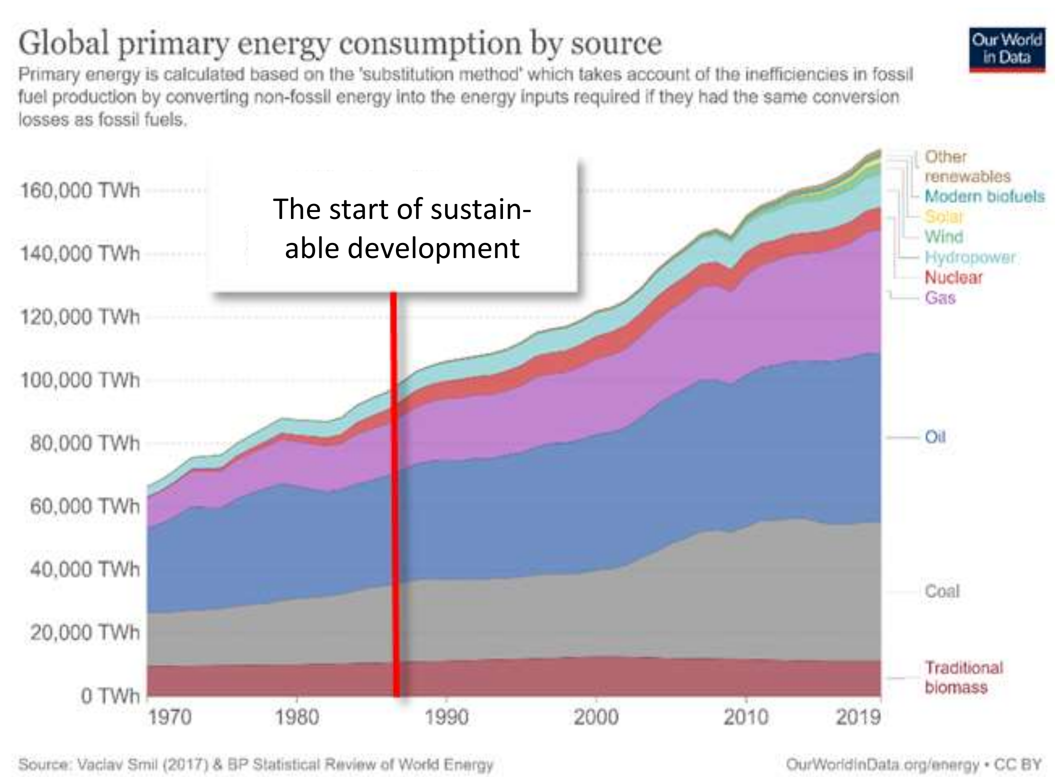

Figure 6: The consumption of every type of fuel has increased since the start of sustainable development, and renewable energy has been added to the energy mix rather than reduced emission

In accordance with the claims of Otero et al., Huesemann&Huesemann and the follow-up simulations to *Limits to Growth*, there is no indication that eco-efficiency is lowering absolute consumption. On the contrary: since more efficient technologies can process more natural resources with less energy—and consumption of every type of fuel has increased at the same time—this increase in efficiency must translate to *increased speed in converting biodiversity and habitat into capital and utility*. A possible paradox of eco-efficiency that has been explored in the literature (Mulder et al., 2011, p. 6).

Ecological gain is obviously realized by abstaining from increasing production when more efficient technologies emerge, and instead use less energy and materials to produce the same amount of goods. Thereby reducing total consumption—instead of the price of commodities.

The theory of eco-efficiency assumes that such absolute reduction will occur as technologies become *efficient enough*. However, there are no specifics within neither eco-efficiency nor sustainable development for when this point of *sufficient efficiency* has been reached. It is an unbounded and unspecified goal, not well suited for guidance or assessment, allowing for similarly unbounded concepts—such as eternal economic growth—to be regarded means towards sustainability.

There are no specified mechanisms within the classical sustainability view for how increased technological efficiency combined with *forceful economic growth* can translate into reducing the human ecological footprint. Instead, the factor of unbounded economic growth seems to transform sustainable development into increased industrial and economic activity—which is the fundamental cause of the problems we are attempting to solve. Market-based strategies towards environmental sustainability thereby seem to increase environmental strain for socio-economic gain, under the guise of environmental concerns. This infinite regress towards ecological collapse must be dealt with by any methodology aiming to produce real solutions to the complex of crises we face.

Addressing this issue in a meaningful way would require a discussion of economic systems beyond the scope of this study. Instead, we want to use the observation for a less comprehensive conclusion, related to methodologies. Namely, that even though it might be unrealistic to change the fundamental functioning of liberal economic markets, a **sustainability *assessment*** of a technology can easily be decoupled from such market mechanisms. This would cause environmental efficiency to be at least ***recognized*** by the methodology**.** Thereby making it more robust to the caveats of focusing on forms of efficiency that are irrelevant to the purpose of a technology (such as the “effectivization” of agriculture, see section 3.7).

4.6 Sustainable Energy

In the case of renewable energy generation, we arrive at a similar situation of realizing ineffective forms of efficiency (section 3.2) if the produced energy *does not replace fossil fuels*. As we saw in the graph over global primary energy consumption (fig 6), the implementation of renewable energy has **not yet reduced any global, absolute emissions**, although some industrialized nations have succeeded in reducing or stabilizing emissions. At least on paper.

In the period from 1990-2008, developed nations claimed to have reduced their emissions by 2% (-0.3 Gt). However, when exported emissions were factored in (1.2 Gt), the true figure turned out to be an 8% *increase* in emissions for industrialized countries (Peters et al., 2011, p. 8905). More recently, the EU claimed a 23% cut in emissions from 1990 to 2018[8]. However, these savings are “more than offset” when emissions embodied in imported goods are factored in (Moran et al., 2018, p. 44).

It has also been pointed out that the Kyoto protocol motivates policies that may even increase emissions. The most attractive industries to export (to achieve national climate goals) are obviously the most energy-intensive ones, and they tend to be exported to countries with ‘dirty’ energy sources. In fact, it has been shown that “coal abundance leads both to a specialization in “dirty” sectors and to an increase of emissions per output when controlling for sector structure: a fossil fuel endowment effect” (Weber et al., 2021, p. 27722), which produces a net increase in carbon intensity compared to producing the product in low-emission countries--directly counteracting the potential savings of eco-efficiency. This hypothesis is further substantiated by de Boer et al., who estimated that imported emissions to the EU could be reduced by 46% if the same goods were imported from low-emission production countries (2019, p. 5).

It could be claimed that there would have been *even more* emissions than the current linear BAU-trajectory if it were not for renewable energy generation. However, huge

[8] https://ec.europa.eu/clima/news-your-voice/news/eu-greenhouse-gas-emissions-down-23-1990-still-implementation-will-have-be-further-accelerated-reach-2019-10-31_en

investments have been made in the energy sector in the attempt of battling global warming, that would not have been placed otherwise. It seems unlikely to assume that the energy sector would have grown equally fast without this investment incentive, and consequently that the energy generation surpassing the linear continuation of the fossil BAU scenario would have been generated anyways. Especially considering that combustion efficiency has increased around 14% since 1987, so that the absolute emissions curve should have flattened somewhat, even for the BAU scenario, absolute emissions are in this respect a somewhat misleading metric for business. The business-trajectory that we in fact have followed is an 'even more business than usual'-scenario, which is not visible in the absolute emissions statistics, due to eco-effectivization. Although, it is visible in the increase of GWP, consumption of raw materials and the state of habitat and biodiversity.

If we do not require true and actual cuts in fossil fuel consumption—disregarding bureaucratic euphemisms—we risk making renewable energy an **addition** to the energy mix instead of performing a **transition**. Thereby aggravating our fundamental technological problem of nature loss to human activity, rather than solving it. This would, however, fall in line with previous energy "transitions".

The introduction of coal never replaced traditional biomass—although the consumption was somewhat reduced. Oil never completely replaced coal, gas did not replace oil, nuclear did not replace gas, and so on. Almost every new source of energy having been discovered is still actively used in today's energy mix (except for a few minor ones, such as producer gas and whale oil). This suggests the uncomfortable conclusion that the addition of renewables to the energy mix has primarily caused an *increase* of human activity, and thus loss of biodiversity—which we have established to be a major threat—possibly surpassing the damage of current trajectories for climate change (Maxwell et al., 2016). This questions whether renewable energy can be considered *sustainable* energy—unless we apply stricter requirements.

If we are to regard renewably generated energy as sustainable in a stronger sense of the word, it must *both* replace some amount of fossil-generated energy *and* the activity it fosters must be sustainable in itself. The degree of success in these two areas defines how sustainable some quantum of energy can be considered.

Further reflection from this point on bring us back to the normative realm of how energy *should* be used—which we cannot pursue further at this time. We can instead make use of the fact that most of the energy we generate is used for making technologies run, thereby allowing these intangible questions to be considered in a more descriptive fashion. In the following, we propose a tentative framework for assessing technological sustainability based on the I=PAT-equation (the mathematical fundament behind the World3-model of Limits to Growth), demonstrating how to derive analytical building blocks for use in the methodology.

5. THE ROLE OF TECHNOLOGIES

Reducing economic growth and decreasing living standards is generally not considered viable options for mitigating the environmental crisis. Instead, the prospect of a sustainable future relies on creating a compensating layer of technologies between human activity and environmental functioning (see section 3). A formalized way to assess this role of technologies can be found through the I=PAT equation which we consider a promising analytical framework for deriving operators for the methodology. It describes environmental impact (I) as a product of population (P) times the level of wealth per capita (Affluence, A), modified by the properties of technologies (T):

$$Impact = Population\ x\ Affluence\ x\ Technology$$

If we expand the terms, we can see the interconnections between societal factors more clearly:

$$Impact = Population\ \ x\ \ \frac{GWP}{Capita}\ x\ \frac{Environmental\ strain}{Technology}$$

This mathematical identity shows how environmental impact is related to the scale of population, the production of goods and the properties of technologies. If we transform the equation in terms of infinitesimals to reflect momentary growth rates, we get the following expression:

$$\frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T}$$

As a first observation, we see that any truly sustainable process needs to satisfy that $\frac{\Delta I}{I} \leq 0$ (non-increasing) to avoid ecologic collapse over an indefinite time span. Now, let us create a quick example to demonstrate more specific usage of the formula: If Gross World Product (GWP) increases by 3% per year due to 1% population growth and 2% economic growth, how must our technologies respond to stabilize the situation? In this case, we get the following solution for sustainability (if the assumed development were sustainable):

$$\frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T}$$

$$\downarrow \quad \downarrow \quad \downarrow$$

$$1\% \;\; +2\% \;\; -3\% \; = \; 0$$

We see that an increase in technological efficiency of 3% every year is needed to compensate for this development. However, at this point we need to remember our discussion regarding efficiency, because this increase cannot be one of *economic* efficiency or solely *energy* efficiency—these metrics infer sustainability only within a neoclassical conception of weaker sustainability. It is the ***actual environmental performance*** that must increase, in line with the reflections on efficiency, effectiveness and purpose in chapter 3.

For example, a 3% increase in the efficiency of solar panels does not automatically affect an environmental impact assessment positively. If the 3% of added energy is used to produce more commodities (rebound effect), there has not been any actual reduction of *environmental* impact. To positively affect the I-PAT equation, the increased efficiency *must* translate to environmental gain and not to increased production capacity.

Let us get a bit more specific in developing the equation further towards this manufacturing aspect of technology and see what it can do. In the following, consider in what way technological efficiency affects the manufacturing level of a technology:

$$Impact = Quantity\ x\ \frac{Pollution\ and\ nature\ loss}{Manufacturing\ process}$$

$$\downarrow \qquad\qquad \downarrow$$

Q $\quad$ ${}^{1}/_{P_e}$ (Production efficiency in terms of environmental indicators)

Here we get an expression of the relation between production efficiency (P_e) and environmental impact (I) , given as:

$$I = Q\ x\ \frac{1}{P_e}$$

If we differentiate this in relation to time, we get

$$\frac{dI}{dt} = \frac{1}{P_e}\frac{dQ}{dt} - \frac{Q}{{P_e}^2}\frac{dP_e}{dt} \leq 0$$

After normalizing and rearranging terms, we get an expression for sustainable manufacturing of some technology:

$$\frac{\Delta P_e}{P_e} \geq \frac{\Delta Q}{Q}$$

where the increase in production efficiency (P_e) must exceed the increase in resource- and energy consumption that the increased production quantity (ΔQ) represents.

Operators such as these make it is possible to describe some of the issues discussed that initiate the slippery slope towards value questions, such as how energy is to be used, but in a more descriptive fashion without making value judgments directly.

For example, consider how P_e and Q are coupled so that technological production efficiency (P_e) can be considered a function of production quantity (Q). For example, by using learning effects and economies of scale as means for increasing production efficiency. The relation can be denoted as

$$P_e = f(Q)$$

This relation can identify cases where it is realistic to assume that more efficient manufacturing processes will in fact lead towards sustainability, in line with the theory of eco-efficiency and other approaches building on ecological modernization. We critiqued the position of eco-efficiency in section 4.5, but from the perspective of considering it a *fundamental solution strategy* for the ecological problem. However, if increased efficiency in fact translates to lowering absolute resource- and energy consumption and thus affects environmental impact (I) positively, then such increase of market efficiency indeed becomes part of the solution.

Unfortunately, the inverse relation exists as well. If increased production efficiency leads to reduced prices and increased demand, then the increase in efficiency translates to increased production (which is the crux of having economic growth as part of the solution). This effect can be denoted by the relation

$$Q = f(P_e)$$

and describes how production Quantity (Q) can become a function *f* of technological efficiency (P_e), so that increased technological efficiency only increases the quantity of production.

This is an expression of the rebound-effect, operational for methodological purposes but with the philosophical side-effect of protecting against technological despair (section 3.6) by making it harder for contextual factors, such as market mechanisms, to implicitly redefine how we perceive efficiency in green technologies. Forcing indicators to be chosen more actively and consciously.

It is important to acknowledged that modern technologies tend to affect *all* parameters of the I=PAT-equation. For example, antibiotics have increased population $(P\ x\ T)$

while also increasing work capacity by reducing sick leave ($A \ x \ T$) and the technology itself has also (negatively) affected the environment ($-T$). So, we would use a version of the equation for the methodology that captures such interconnectedness, as proposed by Huesemann&Huesemann (2008, p. 789) in the following format:

$$I = (P \ x \ T) \ x \ (A \ x \ T) \ x \ T$$

This is as far as we get on developing a tentative mathematical framework for the methodology in this preliminary study. The conceptual importance of this approach is that it requires the success criteria for the efficiency of green technologies to be given in metrics of *environmental performance*, rather than neoclassical indicators (increased GDP) or market indicators (low LCoE). Technologies must be decoupled from the economic externalities embedded in these indicators to evolve towards increased ecological sustainability. If not in practical reality, then even more importantly on a methodological level.

The specifics of how to include these parameters into an overarching framework for technology assessments is very challenging and must be done in a main project. At this point, we merely attempt to derive a few conceptional building blocks and argue for their practical usability. In the following, we will try to make use of the ground we have covered to develop such an overarching framework capable of avoiding the caveats we have attempted to illuminate philosophically.

6. THE METHODOLOGY

We have listed three steps below that constitute a prototype for the overarching framework of the methodology, that we believe capable of judging the efficiency of green technologies by a relevant conception of efficiency. The first step is to identify the *potential* for synergy that a technology inhabits:

1. <u>Identify Potential Synergy effects (evaluation of the technology)</u>
    a. Analyze the properties of the technology, relative to a consciously chosen relative base. We consider ecological science a suitable such basis.

   b. Count all possible synergy effects that can be realized between the technology and the reference base.

This will result in sets of positive and negative synergies that have not yet been manifested. Consider it a ‘blind’ sustainability indicator, providing a crude assessment of the potential of a technology *in itself* to be implemented sustainably—disregarding context. Any such potential must be paired with suitable conditions in the implementation context, before the real and physical synergy effects emerge. The second step thereby becomes to identify *synergy partners* in the implementation context:

2. Identifying synergy partners (evaluation of the implementation context)
   a. Consider a specific implementation site, or a general type of area relevant to where the technology will be used
      i. Correlate the potential synergy effects identified in step 1 with synergy partners in the given context
      ii. Count the number of actual synergy effects that are possible to manifest.
   b. This provides a crude assessment of actual systemic impact. **Note that this evaluation is still discrete, without the weights needed for a graded result**

These two first steps together produce a philosophical solution for the fundamental problem of technologies, which we have considered to be the most important requirement for a methodology of sustainability. The third step is to assign weights to the realized synergy effects, where a graded sustainability score eventually can be established:

3. Weighting realized synergy effects
   a. The realized effect from a synergy/partner-pair needs to be scored
      i. Neutral synergy effects have zero as their coefficient and are removed from the equation
      ii. Negative synergies get a score <0
      iii. Positive synergies get a score >1

b. When these weights are assigned to the impact-equation of the methodology they produce a graded score for the sustainability of different technologies (when implemented in the same or similar context(s))

Further research is required to establish whether a certain score can be labeled “green” or “sustainable”, or if the methodology to a larger extent is a guide for arriving at an expert opinion through a systematic process.

6.1 Examples

We are going to walk through one step-by-step application of the sustainability assessment algorithm and then provide two examples that illuminate different conceptual aspects of the approach.

Example 1: Wind turbines

1. Implementing small wind turbines on- or near existing infrastructure produces the following synergies:

    i. Eliminates loss of ecological space (+1)
    ii. No need for high-voltage lines from the production site to end-users (+1)
    iii. This, in turn, eliminates the need for transformer stations (+1)
    iv. Lower voltages eliminate the need for SR-6 gas for insulation of high-voltage equipment (the most climate-sensitive gas known, with 23 500 times more heating potential than CO_2) (+1)
    v. Greater geographical dispersal of generators evens out peaks and valleys of energy production, if implemented on a large scale, since local weather conditions will differ, compensating for one of the main challenges of renewable energy systems (+1)
    vi. Local businesses and personnel can maintain and repair turbines due to the low voltage and less demanding equipment (+1)
    vii. However, less energy is produced per turbine due to the exponential relationship between tip length and energy production (-1)

viii. Requires metals that are currently mined in unsustainable ways (-1)
ix. Parts are made of composite materials that are not easily recycled (-1)

x. Synergy indication = [6,-3]

2. Large parks of large wind turbines produce the following synergies:

   i. Produces energy more efficiently relative to the material base per turbine (+1)
   ii. But needs ecological space for implementing the turbines (-1)
   iii. Needs ecological space for roads (-1)
   iv. Needs heavy equipment for repairs (-1)
   v. Needs specially trained personnel to maintain or repair (-1)
   vi. Requires SR-6 gas for switching gear (-1)
   vii. Requires substations for stepping up and down voltages (-1)
   viii. Requires dedicated transmission lines (-1)
   ix. Requires metals that are unsustainably mined (-1)
   x. Parts are composite materials that are hard to recycle (-1)

   xi. Synergy indication: [1,-8]

Now remember: this 'blind' evaluation of synergy *potential* does not provide any answer as to which technology is 'right'. The only information that can be derived directly from this evaluation is that the technology with the higher synergy score is more flexible and easier to implement in synergic ways. However, the actual sustainability score is dependent upon the implementation site, so before a judgment can be made, we must apply step 2 and analyse the implementation site:

Let us in this case assume that the implementation site is a rocky desert with very low biodiversity, located relatively close to a large city. In this case, all the negative synergies of large turbines might very well be outweighed by the one positive synergy effect of increased power output per device.

To evaluate this and arrive at a conclusion, step 3 needs to be actuated. Here, each synergy effect is assigned a graded weight, so that the overall systemic efficiency can be compared to the case of maximizing individual efficiency. A complete answer would require a much more comprehensive analysis and a well-developed system for which synergies to include, as well as how to assign weights (tasks for a main project). However, we will provide a simplified example to demonstrate the conceptual way of thinking:

Technology: Small HAWT's	**Technology:** Large HAWT's
Context: low biodiversity, close to consumers	**Context:** low biodiversity, close to consumers
+(1.16 x habitat loss)	- (1.15 x habitat loss)
+(1.13 x biodiversity loss)	- (1.12 x biodiversity loss)
+(1.11 x no transformer stations)	- (1.11 x transformer stations)
- (1.09 x many low voltage inverters)	+(1.09 x no low voltage inverters)
+(1.23 x transport grid)	- (1.20 x transport grid)
– (6.0 x individual efficiency)	+(6.0 x individual efficiency)
= 3,55 - 6 = - 2.44	= -3,50 + 6 = + 2.51

For this specific case, we see that large horizontal axis wind turbines would be best for the implementation site in question. The gain from the one synergy effect of more output per turbine outweighs the systemic optimizations in this context. If the implementation area had been biodiversity rich and/or if the generation site was very far from where the energy was to be used, or the winds were rapidly changing, the outcome could change.

A defining trait for conventional technologies is that they maximize one or a few synergy effects through comprehensive support systems. The efficiency of complex technologies tends to be manifested by systemic optimizations, by utilizing a range of synergies. We are accustomed to thinking that individual efficiency generally outcompetes systemic advantages. However, as the following example demonstrates, it is possible for low efficiency devices to outperform radically more efficient devices—if the degree of synergy is very high and the ecological footprint very small—or even capable of contributing positively to ecological functioning.

Example 2: Photovoltaics vs. Photosynthesis

1. Industrial solar cells are ~23% effective at transforming sunlight into energy
   i. Plants are on average around 1% efficient for the same task
   ii. Solar cells are thereby 23 times «more efficient» than plants
   iii. Does this make solar cells «better» than plants…?
2. However, even at their modest 1% efficiency, plants produce most of the resources for living, for economic trade and for human well-being. **How is that possible?**

Plants exploit a plethora of systemic advantages to help increase their overall efficiency by synergically interacting with their surrounding ecosystems. They extract CO_2 from the air while converting sunlight into biomass, which again provides feed and shelter for animals, and nutrition for microorganisms. These interact symbiotically with mycelium and fungi in the soil to generate further nutrients, especially adapted to the needs of the interconnected fauna. The process generates chemical energy, habitat and resources for every complex land species on the planet—as well as most of the raw materials involved in generating the revenue of the global market. All while maintaining a fertile soil! The byproduct of the process is the oxygen we breathe. A truly green and sustainable process, which also has been sustained for hundreds of millions of years.

This is value creation is sustainable in every link of the chain. Even economically. The value creation of nature is estimated somewhere around $125 trillion/year--or almost three times the global gross domestic product (Costanza et al., 2014, p. 156). This estimate comes with its share of uncertainties but establishes a methodological baseline from which it is possible to indicate the monetary costs of nature loss, which seems to lie somewhere between $4.3-20.2 trillion/year over the period of 1997 to 2011. Equating to a mean loss of 10,6% of the 2011 global GDP (Ibid.).

It is hard to assess the accuracy of these figures (hence the large prediction interval) but it demonstrates the vast potential for value creation from implementing technological solutions in synergic ways. Since vegetation is generally positive for ecosystems and not a burden, there are no restrictions for the area that can be involved in vegetative value generation. Consequently, plants do not *need* to be more than 1% energy efficient to create the majority of value, well-being and wealth on the planet. In the same way, technologies do not need to function at maximized efficiencies—*if* they have low environmental impact and function synergically with ecological systems.

We see here how vegetation regains "lost" efficiency, due to the exceptional degree of synergetic efficiency. And this is how we need to think when developing the next paradigm of green technologies! As a last example, related to scaling, consider the following concerning hydropower plants.

Example 3: Scaling of hydropower plants

The Aswan High Dam in Egypt was an attempt to provide large amounts of energy in environmentally benign ways, by pushing the boundaries of scale to maximize efficiency. The costs of the project exceeded $1 billion and involved a 10 GW hydroelectric powerplant in addition to reconstructing 700 000 acres from flood- to canal irrigation, which was believed to double or triple cropping in the farmland. However, the dam instead triggered a cascade of unintended consequences:

1. Loss of river water flushing salts from the soils required the construction of an extensive network of drainage tile systems. **Expense: $1 billion.**
2. Drastically reduced sediment transport, causing loss of soil-building and natural fertilization in the Delta. **Expense: $100 million/year** of additional chemical fertilizer being required downstream of the dam (a five-time increase). Keep in mind that nitrogen is extracted mainly by help of natural gas, causing CO_2 emissions, and both Kalium and Phosphorus are mined resources. These factors work against the dam's positive environmental effectiveness.
3. Increased salinity and seawater intrusion in the Delta.
4. Coastal erosion.

5. Increased riverbank and bottom scouring, threatening the integrity of more than five hundred bridges built in the decade before the dam, requiring mitigating measures. **Expense: $250 million.**
6. Reduction in plankton and organic carbon levels in the Mediterranean (which traditionally has sustained a large and productive sardine fishery).
7. Less water downstream due to evaporation and seepage.
8. The dry periods between floods limited the prevalence of water snails, which carry schistosomiasis—a debilitating disease which ended up affecting a significant proportion of the rural Egyptian population, after the dam was built.
9. The fisheries around the mouth of the Nile Delta eventually collapsed. At first, it was reversed during the '80s due to the dual impact of chemical fertilizer and sewage runoff causing a surge in nutrient levels and hence fish populations. But then declined once again, due to eutrophication (low oxygen) caused by the accumulated impacts of the aforementioned discharge.

(Nemetz, 2022, pp. 39–40)

In retrospect, the Aswan project could have been scaled down considerably, or been expanded with comprehensive systems for ecological synergy, without any actual losses of economic efficiency. Simulations of economic advantages from watershed management indicate that the net economic advantages of just facilitating sediment flow would accumulate to $500 billion over the 500 years expected lifetime of the dam (Lee et al., 2011, p. 11).

But why are these economic expenses of ecological dysfunctionality so visible in the case of the Aswan dam, while seemingly intangible in many other projects? The effects become apparent because of the long lifetime of the dam. During a 20-year investment return scheme, many such expenses due to ecological malpractice do not become evident—although they are no less real. We clearly see how the investment perspective of 500 years automatically brings economy closer to ecology.

This in mind, consider the prospect of small hydroelectric power plants designed not to disrupt ecological functions, compensating for lost conventional efficiency by increasing systemic efficiency. If scaled optimally and constructed in line with a comprehensive understanding of the ecological function of a river (which was not well developed when the Aswan dam was constructed in 1965), it might even be possible to increase ecological performance and economic efficiency at the same time through synergetic thinking.

1. Such a strategy would involve small or no dams, allowing for seasonal variation in water levels, which is vital for biodiversity at riverbanks.
2. On the negative synergic side, hydropower loses some crucial benefits by not storing large amounts of water (predictability of power supply, grid compensation, energy storage etc.). However, this challenge must, in any case, be solved globally by new battery- and/or storage technologies.
3. If power generation did not strain river ecosystems past their resilience levels (tipping them into new equilibria), far more micro-hydro power plants could be built.
4. How should such pros and cons of hydropower scaling be weighted sensibly? The ARC Methodology could clarify such questions and facilitate assessments of the trade-offs involved and possibly suggest optimal designs and scales for extracting the maximum amount of power within the resilience of a given river ecosystem.

Some power or some amount of resources can always be extracted from an ecosystem without straining it past its resilience limits, allowing it to gravitate back to its initial conditions rather than tipping into some new state of equilibrium (Nemetz, 2022, pp. 29–31), as happened with the Aswan High Dam and several connected ecosystems. Could it even be possible to design micro-hydropower plants capable of producing power while contributing positively to the ecological functioning of a river? For example, continuously calcifying Norwegian streams that still suffer from the after-effects of the acid rain of the 90s or providing an optimal stream of water for salmon to climb during mating season, and thereby increase the procreation rates of salmon—becoming positive components of a river ecosystem instead of sacrificing ecological functioning for maximizing the output of power.

Studies on the North Pacific and Alaskan salmon revealed that over 130 species depended on their life cycle (Cederholm et al., 2000). A reduction in salmon population past resilience levels would initiate a cascade of repercussions throughout the ecosystem, affecting everything from river microbial life to tourism income for businesses (Nemetz, 2022, p. 37). Inversely, if a technology affected the life cycle of salmon positively, this seemingly inconspicuous consideration could compensate for significant reductions of individual energy output.

The ARC Methodology could potentially be developed to provide a systematic way to assess such somewhat unintuitive and intangible tradeoffs, that tend to escape current assessments. If the efficiency gained from positive synergy was factored in and make visible, better judgments could be made for the trade-off between individual maximization and systemic optimization.

If combined with input from the Stockholm Resilience Center and similar institutions that provide data on planetary constraints, specific and concrete synergetic thresholds could be worked out for the optimal scale of a technology, or the optimal degree of utilization of some resource; such as fish farms, mining operations, wind parks, solar plants and more. The methodology could also provide suggestions for increasing systemic efficiency in existing installations.

Work is needed to generalize how much lost individual efficiency that can be regained by systemic optimization, so that measures can be developed for such optimization. But if this is done, we firmly believe that this conceptual approach can be developed into a methodology **that is capable of giving good reasons why some technology or some solution would be 'right' for the green transition, compared to some alternative technology.**

6.2 Economic comparability

To measure the true economic gain of increased systemic efficiency (between technological and ecological systems), the results would have to be assessed within a suitable economic paradigm. As stated by H. T. Odum, "[m]oney is only paid to people and never to the environment for its work (…). Therefore, money and market values cannot be used to evaluate the real wealth from the environment" (1996, p. 55). Bluntly put, for our purposes: the rewards of resource- and energy efficiency need to be measured within a system that in fact does reward such efficiency. Which is not the case within current market paradigms, that broadly reward environmental destruction and even may consider it sustainable—if only aggregated income increases over time (the neoclassical requirement for sustainability).

An economic paradigm ridden with externalities cannot recognize the environmental advantages of ecologically sustainable technologies. To compete on *price* against technologies that exploit externalities – within an economic system that rewards such externalization – green technologies are forced to exploit externalities as well. Only *others* than fossil fuels do, specifically, externalizing costs onto habitat and biodiversity instead of the atmosphere.

For long-term systemic profit to be recognized in economic models, the effects of technological-ecological synergy would have to be assessed within a simulated economic environment suitable for the task. One that compensates for economic externalization and rewards energy- and resource efficiency. The losses of renouncing economic externalization could then be turned into at least *simulated* profit for the sake of an unbiased assessment, making the economic efficiency of sustainable technologies comparable to conventional solutions—and on fair terms. From there, policymakers could choose consciously and actively in an informed manner.

Due to the relation between synergy and thermodynamics, these assessments are also likely be compatible with the philosophical fundament behind ecological economy or -engineering, as established by Odum & Odum, Daly, Pimentel, Jansson and others. Output from the methodology could thereby be further processed through these frameworks to an economically functional technological solution.

Today, we routinely scale up technology systems in pursuit of economic efficiency to proportions that conflict with ecosystem functioning. However, there are cases emerging where it is acknowledged that complex solutions would have worked better. India's large-scale implementation of solar has suppressed the more complex integration of rooftop solar[9], and due to misclassification of nature types several 500-MW installations were built in areas of high ecological value (Madhusudan & Vanak, 2021). India is now

[9] https://india.mongabay.com/2021/08/is-indias-rooftop-solar-sector-being-ignored-for-large-scale-projects/

considering complex integration schemes as real competitors for mega-sized projects. In this case, following the algorithm of the ARC methodology would likely have discovered the negative ecological impact of these mega-sized sun parks by analyzing the implementation sites relative to the properties of the technology.

Before concluding the study, we will provide two case analyses that demonstrate how the methodology analyzes more conceptual aspects of technology systems.

6.3 Case analysis 1: Coalifying CO_2

At the RMIT-University of Australia a method for converting CO_2 into coal is developed as a safer means of storage than gas-based CCS[10]. The method dissolves CO_2 in a gallium alloy electrolyte liquid, splitting carbon dioxide into solid carbon (coal) and oxygen gas when current is passed through.

In an interview, the researchers state that '(…) the reaction takes about as much energy to restore the carbon to solid form, as was released when it was burned'. Considered from a physical perspective, this means that the thermodynamic efficiency of the reaction is zero percent—as expected from a reversed chemical reaction (ignoring the losses from non-ideal conditions). However, they further state that '(…) as the **cost** of renewable energy continues to drop, this may prove an ***effective*** way to deal with captured carbon dioxide'. This assumption does not make philosophical or physical sense.

The *physical* notion of efficiency is being mixed up with the economic notion of efficiency in the evaluation of the *effectiveness* of the technology. The chemical process obviously does not perform above 0% *thermodynamical* efficiency, even though the monetary price for renewable energy is lowered enough to generate profit. Such profit merely indicates that habitat destruction is devalued to such an extent that it has become economically viable to use renewable energy for producing coal (helped by financial mechanisms such as carbon taxes and subsidies for CO_2 removal). If biodiversity and habitat were ascribed a price, the method would no longer be considered efficient.

[10] https://www.cbc.ca/radio/quirks/mar-2-2019-the-goodness-paradox-secrets-in-poop-converting-carbon-to-coal-and-more-1.5037008/creating-coal-from-co2-undoing-fossil-fuel-burning-to-save-the-climate-1.5037028

From a systemic point of view, the most physically efficient solution is to leave the same amount of coal that this technology could produce over its lifetime—in the ground. This solution would be beneficial in several aspects: It would eliminate the habitat- and biodiversity loss from mining gallium for the chemical process and the rare earth metals for renewable energy generators. It would have saved the ecological space needed for energy installations and saved space and resources of factories to coalify carbon—as well as the arrays of scrubbers for Direct Air Capture (DAC) of CO_2. This technology is "efficient" only when considered within an economic context and "effective" only within a *very* weak sustainability paradigm that ignores biodiversity and habitat.

Compared to stranding assets, the technology itself does not provide any thermodynamical or ecological advantages. The researchers seem to be oblivious to this fact, as well as to the change in academic basis that they commit when moving from natural sciences (their area of expertise) to market-economic assessments (which is *not* their area of expertise). They cross critical philosophical boundaries that lead to crucial factors being ignored in their evaluation of effectiveness.

From a top-down view, the technology effectively uses renewable energy and rare earth metals to convert habitat and biodiversity into coal. However, this ecological fallacy is not visible to the scientists. Instead, they consider the next logical step to <u>scale up</u> this system, boldly stating that "(…) we **don't see any problem** with why this can't be rolled out on a **very large scale**".

There could be some application for this technology to limit local emissions by installing it directly in factories. However, since CO_2 is diluted evenly in the atmosphere and does not have any local or acute toxic effects (optimal CO_2 levels for most plants is, after all, around 1200 ppm), it is hard to see the advantages of spending extra energy, resources and ecological space on solidifying burnt carbon—rather than not burning it. Unless the generation of renewable energy is regarded to be 'consequence free'—which we have established that it is not. The captured carbon must be *utilized* in some way that reduces *other types* of resource consumption (establishing ecological synergy by connecting the process to some ecological circularity) before this technology would be environmentally effective—and thus a green technology.

6.4 Case analysis 2: The Finnfjord Smelting Plant

A successful example of synergy in existing ARC-projects is the Finnfjord smelting plant, where algae is used to extract carbon and toxic pollutants from factory smoke, converting them to edible and healthy algae mass. This product is then sold as fish feed for farms, providing new business opportunities for the factory while also reducing emissions.

If this salmon fodder replaces fodder made from unsustainable sources (soybeans/fished resources), the technology can reduce resource consumption in a way that satisfies all three dimensions of sustainability while also respecting the ontological coherence of the term.

The smelting plant is also installing the biggest non-commercial steam generator in Norway (340 MW) to reuse heat that escapes from the smelting ovens, thereby increasing the thermodynamic efficiency of the plant while lowering the cost of operation and reducing external energy dependency.

An example of how additional and unexpected synergies may emerge, as a complex system of synergies grows, was observed in the Finnfjord-project. It turned out that fish that were fed with these algae became less prone to salmon lice infestations, in a preliminary small-scale study[11].

As shown in the coalifying example, the evolution of 'green' technologies suffers if technologists and natural scientists feel compelled to replace their deep understanding of physical efficiency as experts in their field, with a shallow understanding of market-based efficiency—without the necessary competence within economy, ecology, markets and philosophy to understand what such a change of efficiency-basis means for the environmental system. The ARC Methodology exposes a range of predictable negative effects that arise when 'green' technologies are assessed from (1) a philosophically incoherent position, (2) through a conception of sustainability that is not operational, and (3) through a notion of efficiency that is not relevant to the purpose of the technology.

[11] https://uit.no/nyheter/artikkel?p_document_id=649503&p_dim=88163&fbclid=IwAR0bPZhpgMliE3IiIKdOII5hpVHrNhMEHoExKyJ5HQwEgxwXbMwBfqEY1Do

7. Conclusions

7.1 Short conclusion

The short answer for how to move towards sustainability in line with our tentative framework, is to integrate all technologies with complex implementation strategies that establish synergy with specifically *environmental* systems (and not production- or financial systems). This would directly address the 'fundamental problem' of sacrificing nature for technological expansion and promote beneficial solutions for both nature and, in the long run, economies.

We consider it feasible to construct a methodology that can score the sustainability of technologies in terms of synergy, and thereby develop implementation schemes that methodically produce systemic advantages that can compensate for some, or even all, of the lost conventional efficiency resulting from increasing the ecological compatibility of technologies. The degree of regained efficiency largely depends on the size and degree of interconnection of the complex system, since more synergy effects will emerge as the complexity of a system grows. So synergic solutions might initially appear less profitable than conventional strategies because the current systemic advantages reward conventional implementation strategies, but as technological systems increase complexity, the economic advantages of ecological compatibility will become evident.

Substantial research is needed to develop this outline for a methodology into a functional assessment tool, but efforts to develop such a methodology would place ARC in the avant-garde of sustainability research. Further work would, in any case, produce an innovative concept for analysis to generate reports/advice/expertise given by ARC, providing new routes for increasing environmental sustainability in renewable energy projects.

The analysis will not oppose economic efficiency but specify the ecological constraints and boundaries that technology systems must adhere to before economic efficiency is a relevant to evaluate. It will also provide suggestions for increasing cost efficiency within these given constraints, only through synergy instead of generating profit by stealing from future generations.

The methodology can be critiqued for being too strict and unrealistic, however, we do not consider such critique to concern the methodology. Rather, we see it as a critique of the idea of becoming fully sustainable in itself. At the current state of global production systems, such a goal is not very realistic and a methodology towards true sustainability must reflect this fact in its demands.

We believe that our methodology can provide realistic assessments of what it takes for a technological solution to evolve towards environmental sustainability—and also to do it at the lowest socioeconomic cost possible. If achieving ecological sustainability is still considered too demanding, it does not change the fact that the demands of the methodology reflect the physical science of what it takes to be sustainable. Such critique is thereby not one the methodology but rather of the prospect of becoming sustainable in itself. If the bar for qualifying as sustainable is lowered beneath what ecosystems require to sustain themselves, due to political reasons, we have arrived at an oxymoronic interpretation of sustainability. Put bluntly, it would severely defeat the purpose of a sustainability methodology if greenwashing were to become an integral part of it.

Taking this stance is part of maintaining high academic standards amidst an immense political pressure of making it easier to be sustainable. Such a no-compromise stance would separate ARC from the bulk of institutions working with sustainability by providing realistic standards for the degree of change that is required for the results that politicians have committed to, through countless resolutions and deals. It is not relevant for a fact if it is unrealistic, and it would not make sense for scientific institutions to comply with wishful political thinking when shaping a methodology stating the requirements for what it takes to become sustainable.

The value choice we are confronted with is not whether to accept ecology as a science or not. It is for a nation or company to choose if it wants to be sustainable or not. Here, it is outside the role of academia to say which choice is right. It is, however, both irrational and wrong to change the concept of sustainability to a degree where it is possible to regard oneself as sustainable while simultaneously moving towards ecological collapse.

Our take home message is that we are out of time to rely on faith-based solutions for solving environmental problems. We agree with recent literature that updated methodologies are urgently needed to steer technological development towards stronger conceptions of sustainability and we believe that our synergic efficiency view is worth exploring further.

It is perfectly possible to provide scientific analyses of what it takes on an ecological level to sustain environmental functioning within certain resilience thresholds. Our analysis would provide constructive advice and suggest practical possibilities for how to optimize economic efficiency within the constraints of the ecosystem, however, through synergy rather than economic externalization.

We believe it to be an absolute requirement for overall sustainability to move away from socio-economic indicators for assessing efficiency in green technologies to achieve the result they are meant to produce—for them to work. Instead, the natural sciences must be considered the basis for finding the solutions for how to keep human impact within planetary boundaries. Thereby leaving the theology of technological salvation behind.

7.2 Detailed conclusion/Summary

Technologies cannot be regarded sustainable as isolated objects. They require a context to interact with (the environment) and resources and energy to function. This means that any large-scale technology system will become a mechanical part of its overarching ecosystem – whether such integration is intended or not. From there, it is logical that technologies must operate from the same basis for efficiency as ecological systems do, if sustainability is to a realistic outcome (in a stronger sense of the concept since weak sustainability can be achieved simply by stating belief in technological salvation).

Conventional technologies are generally produced and integrated in ways that are incompatible with natural systems, thereby causing ecological problems (such as climate change and biodiversity loss). Additionally, current growth-based economies reward time efficiency over energy- and resource efficiency, even though it is less thermodynamically efficient to work against natural systems than to work with them. Thereby contributing to pushing technological evolution toward negative environmental synergy.

Technologies provide for human needs. The defining trait of green and sustainable technologies is to provide the same functions and services as ordinary technologies, but in benign or even advantageous to natural systems. If market mechanisms evolve green technologies towards less environmental sustainability, for the overarching goal of increased economic profitability (from strong to weak sustainability), then they will evolve away from their purpose and in the end seize to differ significantly from conventional technologies. The most important task of a methodology is to avoid this convergence of green technologies into conventional machines, only driven by renewable energy instead of fossil fuels.

The resilience of ecosystems dictates the amount of human activity possible to sustain before overshoot is a fact, which leads to inevitable ecological collapse sooner or later. If technologies are to be part of the solution, they need to operate within ecological tolerance levels. To consider ecological effectivization in terms of economic cost is borderline irrational when considering that any wasted energy, resource or reduction in regeneration of natural resources will diminish the total amount of trade within a finite and regenerative resource base.

The only way to increase value creation is by increasing value generation. The only way to truly expand the economy is to increase regeneration rates of natural resources (a *Regrowth* economy). Any increase of economic profit past ecological resilience levels is nothing but stealing from future generations and does not translate to profit on larger time scales—as shown by the 500-year investment return period of the Aswan High Dam.

Establishing synergy will optimize the usage of existing resources and can potentially increase regeneration rates by utilizing advanced ecological strategies for technology development. Technologies that function in synergy with natural systems do not oppose economic interests but represent a win-win situation for economy and ecology, allowing for more human activity without causing ecological collapse. Analogous to how a meager 1% average efficiency of photosynthesis can produce every renewable resource on earth together with 75% of all jobs—and most raw materials for the commodities we trade (at an estimated value of $125 trillion/year)—we infer that similar advantages can be obtained by using complex implementation schemes to integrate sustainable technologies with ecosystem functioning.

Such a practice would also lower the investment costs for starting new ventures. Today, the massive scales of most renewable energy projects prohibit many low GDP countries from starting their own projects, even though many have much better conditions for generating renewable energy than western countries do (especially solar energy). Complex integration of small-scale renewable energy systems can happen incrementally and requires very low initial investments (principally, one solar panel, a battery and an inverter). This would contribute to leveling out some of the economic inequality between developing and developed countries—which was the main argument behind why the classical concept of sustainable development chose to rely upon "forceful economic growth" to achieve (mainly social) sustainability. After facing the unintended consequences of large-scale projects, India is currently pursuing such approaches to reach their large-scale renewable energy goals. Nations and global institutions might have to defer such economic transformation, but the assessment of green efficiency on a theoretical level does not.

In light of how the empirical data since 1987 indicate increased resource and energy consumption per capita as well as increasing economic differences as the (unsurprising) result after forty years of growth-driven sustainable development, we strongly recommend *not* injecting the same practices and principles into the development of green technologies. Instead, assess descriptively whether they are effective at their distinguishing purpose, and solve the value dilemmas that emerge through the political realm within the planetary constraints that have been established.

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8. APPENDICES

APPENDIX 1: ESTABLISHING SYNERGETIC SUCCESS-CRITERIA

We have argued that a method cannot and should not take a weak stance on sustainability as a starting point. We have tried to make a case that the current theoretical fundament for weak sustainable development is not likely to produce the results that are intended, backed up by the fact that the past 30 years of following this strategy has only sped up resource consumption and energy use. Hopefully, our argumentation has at least succeeded in making the reader open to considering different views on the matter, as we will now introduce our conception of synergic efficiency. But first we need to further formalize synergy effects to make them suitable for analytical purposes.

1.1What are synergy effects?

Synergy effects are often informally described as "that which is more than the sum of parts", a problematic conception in a reductionist perspective. A better formulation that provides broader compatibility has been coined by Anjum and Mumford, as being *different* properties or functions to emerge from a constellation of parts. They call these emergent phenomena:

> (…) emergent phenomena are those where wholes have [properties] that are not possessed by their parts. It is tempting to say that, for emergent cases, wholes have more [properties] than (the sum of) the parts, but we will see that this would not be quite right. It is, rather, about the wholes having different [properties], where we mean not merely the sum of the [properties] of the parts, and nor a mere subset of powers thereof.
>
> (Anjum & Mumford, 2017)

How do synergy effects—or emergent phenomena – differ from analytical parameters for an assessment? An essential trait of synergy effects is how they accumulate information from lower levels, so that they contain all information underlying some complex interaction. Thereby, all information of a system is preserved in a synergy effect, since it is an 'end result' of some process. This is different from a reductionist strategy of modelling a system, first by reducing all information into basic constituents, then assuming some initial condition and further establishing a theory for the evolution of the system. When using synergies as basic parameters, we are using end results directly as parameters rather than constituents of initial conditions, together with a theory for systemic evolution. The problem is that this theory of evolution needs to be correct, in order to not lose vital information.

1.2The holistic versus the analytic

The concept of synergy is often thought of as holistically based and a rather intangible concept. Not suitable for analytical application and often thought to be restricted to biocentric views and environmentalist argumentation. However, rigorously explored synergy effects can be found throughout physics and natural sciences in general (Jaffe & Febres, 2016a, p. 1). For example, atoms have properties that their constituents (protons, neutrons and electrons) do not inhabit on their own. When these subatomic particles are brought together in different constellations, they produce a myriad of different synergy effect for each different atom they form. These "new" or *different* properties are *irreducible* to their parts, which means that they cannot be derived purely from knowledge of subatomic particles. And the same goes for interaction between atoms, for example, oxygen and hydrogen produce the substance 'water', which has properties that neither oxygen nor hydrogen have by themselves. They are both very flammable, while their synthesis is non-flammable.

Since these effects are not analytically deductible from the properties of atoms, the field of chemistry has emerged mostly from experiment. On the opposite end of the spectrum of physics, we see how particle physics also revolves around categorizing synergy effects, specifically those between quarks.

A general weakness of LCA's follows from their strict adherence to reductionist forms of analytical reasoning. When models of complex environmental systems are constructed, we assume that we know enough about their mechanics to provide a correct theory for system evolution over time. However, unforeseen consequences of technology implementation are routinely encountered, and can increase the costs of projects significantly. For example, the Aswan dam in Egypt has obstructed the flow of natural fertilizer, so that farmers below the dam now spend $100 million every year on artificial fertilizer (Nemetz, 2022, pp. 37–39). We obviously do not know enough of the ecosystem to predict effects of large-scale changes over short time spans.

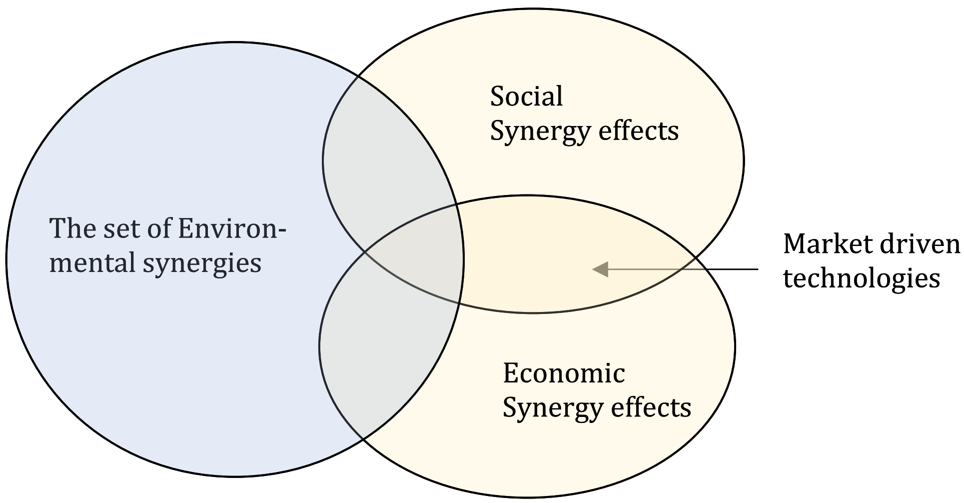
LCA's attempt to predict overall sustainability directly from (too) primitive environmental parameters without a complete understanding of ecosystem mechanics. Thereby ignoring layers of accumulated information between different 'levels' of natural systems. As with the example of how chemical reactions cannot be deduced directly from particle physics (in fact, often not even from nuclear physics), ecosystem reactions can seldom be predicted from a small selection of primitive parameters. Too much information has been lost during the reductions to lower-level indicators. This lost information will be preserved when using synergy effects directly as parameters in a methodology.

Some of the point of this demonstration is to soften the view that holism stands in opposition to reductionism and show that analytical methods can easily use wholes, represented as synergy effects, as indicators. They only need to be categorized in distinct and countable ways. Holistic approaches to problem solving tend to be rejected by anthropocentric paradigms. Thereby excluding holistic and biocentric approaches to sustainability, due to this conceived incompatibility. But the 'holistic problem' of how the complex relates to the analytical is no more necessary to solve for a sustainability methodology than it is for chemistry or particle physics. Instead, parameters and indicators must be structured so that they are compatible with both paradigms. As natural sciences have done to particles and atoms by categorizing them in **distinct and countable** ways.

1.3Deducing favorable synergies

If we start out from the orthodox model for sustainability but let every circle represent sets of synergies rather than abstract concepts, we can define sets of favourable synergies for the purposes of a green transition. Since the development of green technologies is closely linked to market mechanisms, their development revolves around synergy effects that can be found in the intersection between social and economic activity, as such:

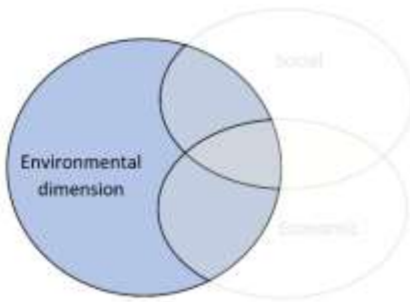
Synergy chart



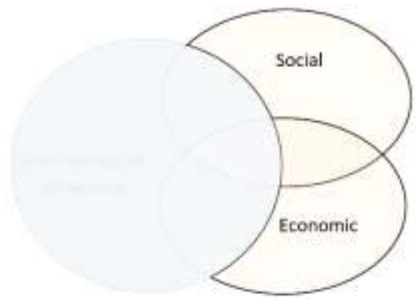
Synergies within the anthropocentric dimensions (between social and economic systems) may produce either strong or weak sustainability. Some interactions can make the system as a whole more efficient, including environmental gain (the WBCSD-theory of eco-efficiency). However, some synergies will make the anthropocentric dimension more efficient in consuming natural habitat by economic and/or social mechanisms. Described initially as the fundamental problem of current technologies, that natural habitat needs to be adapted to their dispositions, rather than the other way around. These synergies need to be excluded from our set of favourable, or right, synergies.

In the conceptualizations below, the area intersected by the environmental dimension (everything blue) contains all synergy effects that promote strong sustainability. All synergy effects outside of this intersection will be either neutral- or negative to ecological interests:

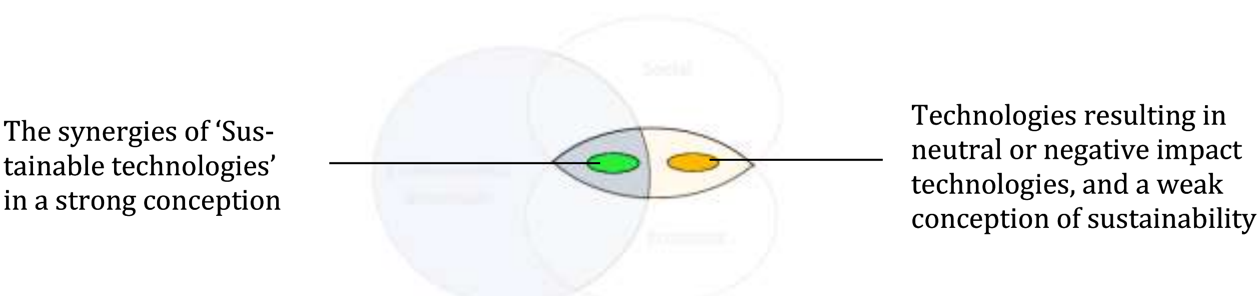
The set of **strong** sustainability synergies



The set of **weak** sustainability synergies



Note that these representations are consistent with the Giddings-model of sustainability, and the principle of assessing all economic and social activity within an environmental frame. From here it is possible to derive a concise analytical definition in terms of set theory, of what can be regarded synergies that lead to the development of sustainable technologies. The set of synergies that are relative to the environmental dimension (after implementation) will constitute strong sustainability. Conversely, the set of synergies produced relative to exclusively social and economic systems are either neutral or negative to environmental concerns. These lead towards a weaker conception of sustainability:



If we adhere to this formalization for which synergies can be regarded 'good' or 'bad', relative to a notion of 'environmental sustainability', we have largely escaped the normative trap, as long as the neoclassical dogma or belief in technological salvation is not invoked (which cannot be invoked in a 'strong' sustainability paradigm). This thereby becomes a relatively neutral way to denote which technological properties that should guide the development of "green" technologies. If the same care is shown to the implementation process, we believe it possible to thereby denote the *right technologies* for the task of promoting ecological sustainability. Which, as previously stated, must be the essential trait of green technologies.

This is not to say that all decisions should be guided by these concerns, which would place our theory all the way into the biocentric position. Our objective is to define a success-criterion that can identify whether technological development progresses towards weaker or stronger conceptions of sustainability. It will be up to policy-makers to choose whether they in actuality want to be sustainable, not a normative task of the methodology.

1.4Will synergy lead to sustainability?

Synergies can emerge between any combination of systems, and the notion of 'positive' synergy as opposed to 'negative' synergy of throws us back into the questions of 'good', 'bad' and 'right'. Metaphysical agreement over the end goal must be presumed to agree which synergy to be "positive", or else one is thrown into an or else one risks establishing a vicious circle of infinite regression over normative questions. In some way, it is necessary to fundament such claims in a concrete fashion (Lie, 2016) In our line of reasoning this would mean to be in agreement over which concept of efficiency to adhere to – which is what we have spent perhaps most time on clarifying during this study.

Our solution is to establish requirements for what the synergies must be relative to—which is why we needed to rank the interior structure of the sustainability term in the first place. So that we could establish a notion of 'right' based upon letting synergies manifest relative to environmental systems. From there, it is possible to also clearly define which properties that will be right for green technologies.

APPENDIX 2: SPECIFICATIONS OF THE METHODOLOGICAL FOUNDATIONS

We have established that a methodology to assess the sustainability of technologies must do so from a strong underlying paradigm of sustainability, that includes the complex interconnections and non-linear factors that characterize environmental systems, and often escape analytically based methodologies. We have reflected over these issues and some core principles for an effective methodology of sustainability, that could be formalized further in a follow-up study:

1. It must as a bare minimum consider the full spectrum of environmental spheres:
    a. The lithosphere (land area),
    b. the hydrosphere (water) and
    c. the biosphere (life) and
    d. atmospheric concerns.

This secures that the methodology does not solve problems by displacing burdens from one sphere to another. For example, from atmosphere to lithosphere by uncritically implementing emission free technologies as 'solutions' for the full spectrum of environmental challenges. From here, we could require our methodology to be explicitly on the strong side of the sustainability spectrum. However, taking an extreme position reduces the utility of the methodology for practical usage.

Even though we have argued for the need for considering sustainability from a strong conception, the degree of realized sustainability will ultimately be up to the choices of policymakers. Since we already have a success-criterion of making technological efficiency compatible with the efficiency of ecological systems, we want the methodology in itself to be blind to underlying paradigms, rather than explicitly embracing one or the other. Instead, considering our favorable sets of synergies as a guiding principle. We aim at building the following further requirements into the methodology:

2. It should be stance-independent towards underlying paradigms of sustainability, and
3. Decoupled from economic drivers of market preferences, and
4. move away from an economic conception of "efficiency"
5. move away from industrial implementation techniques

The notion of sustainability surpasses questions of emissions from production and operation of technologies, as LCA's tend to categorize, and must also include sensitivity to contextual elements such as:

a) how we integrate and use these technologies in natural systems,
b) which economic paradigm we use to calculate their "efficiency" and
c) how the renewably generated energy is used.

This is probably not an exhaustive list, but for the purposes or this feasibility study, they will suffice to demonstrate our approach. We consider the basic indicator of establishing synergy effects as capable of satisfying these basic requirements, and thereby suitable as parameters for a sustainability assessment methodology. Synergy effects are physical, real and countable, and we claim that if the synergies between technologies and their implementation sites are mapped out relative to a basis of ecology and natural sciences (rather than economic theory), is possible to expect overall environmental sustainability as a result.

APPENDIX 3: COMPLEX INTEGRATION

The efficiency of any system increases due to synergy (Jaffe & Febres, 2016b), and new synergies emerge as complexity rises. A technology can adhere to many LCA-criteria for sustainability but still be realized as unsustainable. For example, if wind turbines and solar panels utilize natural habitat for both mining minerals and constructing large energy-parks, the environmental gain of reduced emissions might still be outweighed by direct damage to biodiversity and habitat, as indicated by Sonter et al. and others. Complex integration is a way to promote strong sustainability in technologies in a way that is also beneficial to social, societal, technological or economic processes (Jaffe & Febres, 2016a, p. 2). An example of this would be urban mining as a complex solution to gather metals. Another is placing energy generating devices on- or nearby existing infrastructures, thereby avoiding loss of habitat, realizing them sustainable in a stronger sense. A third example would be to scale down the size of energy generating devices, so that the energy can be fed directly to the low-voltage grid, thereby eliminating the need transformer stations and transportation grids for high voltage electricity.

This strategy would also produce the synergy effect of cancelling out some local weather differences, if spread over very large areas, eliminating some peaks and lows in energy production.

Smaller devices tend to have a lower absolute efficiency of production, but a complexity analysis could show what degree of complexity which would be needed for the disadvantages to be outweighed by systemic advantages, by emerging synergy. To do this we would need a way to formalize complexity over a wide variety of systems, from physical systems to social, economic and societal systems:

TABLE 1

Impact of Synergy Estimated for Several Type of Systems using a Proxy Estimate of Free Energy or Useful Information to Perform Work (W) and the Negentropy of the System (N)

Example	Entropy Measure	W Measure of Work Output	Ω (w) Ratio W	Ω (N) Ratio Negentropy	Ω (w)/Ω (N)
1a	Social Complexity in Myrmicinae ants	Efficiency in energy consumption	1.70	2.00	0.85
1b	Social Complexity in Attini ants	Efficiency in energy consumption	2.00	2.20	0.91
2	Social complexity in aggregates	Exponent of energy efficiency function	2.50	2.60	0.96
3	Scientific development	Economic development	2.60	3.10	0.84
4	Division of labor	Economic efficiency	2.96	3.00	0.99
5a	Brain Complexity	Polymorphysm	2.70	4.00	0.68
5b	Brain Complexity	Log Colony size	3.00	4.00	0.75
6a	Spanish text	Readability	1.05	1.14	0.92
6b	English text	Readability	0.93	1.06	0.88
6c	Spanish text	Nobel Prize/average	>1	1.14	–
6d	English text	Nobel Prize/average	>1	1.06	–
7a	Entropy in music	Popularity	>1	1.04	–
7b	Entropy in music	Number of instruments	>1	1.10	–

Data is presented in unit-free scalars calculated from as the proportional change (Ω) in the system after the synergistic process divided by the value before this process.

The table above shows how Jaffe & Febres have calculated different degrees of complexity in relation to thermodynamical efficiency over very different systems, from ant-colonies and human cities to the efficiency of writing styles in Nobel prize winners, compared to normal writers. Demonstrating the thought of how very different forms of complexity can be formalized into *one* parameter, which is also related to a thermodynamical notion of efficiency (which makes it compatible to environmental economics and similar frameworks focusing on environmental efficiency).

It would be the task of a continued project to include these factors with the I=PAT-equation, but on a very general level we would exploit the effect of increased complexity making any pillar of sustainability more efficient, so that the parameter could be included as a global variable in the I=PAT-equation, as such:

$$\boldsymbol{I}mpact = (\boldsymbol{P}opulation\ x\ \boldsymbol{A}ffluence\ x\ \boldsymbol{T}echnology)\ x\ \boldsymbol{C}omplexity.$$

Or simply:

$$\frac{\boldsymbol{I}mpact}{\boldsymbol{C}omplexity} = \boldsymbol{P}opulation\ x\ \boldsymbol{A}ffluence\ x\ \boldsymbol{T}echnology$$

since impact can be reduced by any increase in complexity in any system. For more specific purposes, the effects of complexity can be limited to just one aspect, such as

$$\boldsymbol{I}mpact = \frac{\boldsymbol{P}opulation}{\boldsymbol{C}_{social}}\ x\ \frac{\boldsymbol{A}ffluence}{\boldsymbol{C}_{economic}}\ x\ \frac{\boldsymbol{T}echnology}{\boldsymbol{C}_{environmental}}$$

These are not finished formalizations; the point is merely to demonstrate the flexibility of the I=PAT-formula and show conceptually how the relation between complexity and thermodynamical efficiency can be used for the purposes of a methodology.

To formalize a way to reap benefits from such synergic thinking, we consider the work of Jaffe&Febres as a promising foundation. We would include these aspects in a possible further main project and create a complexity parameter to be used in conjunction with the I=PAT-formula. Currently, the equation considers absolute measurements of cost and gain relative to the parameters chosen. We would like to extend it to consider *the way* we implement technologies as well.

APPENDIX 4: CONNECTION TO EXISTING FUNDAMENTS

The general lines of our approach are analogous to the fundament for ecological economy (Odum, 1996) where all interactions are also reduced to one parameter. In their case to thermodynamical representations. More recently, this approach has developed into the notion of ecological engineering (Odum & Odum, 2003) which addresses many of the practical challenges that our methodology will face as well. Our approach differs from ecological economy and -engineering by synergy effects being real and physical, and directly connected to the phenomena they describe. Ecological economy and engineering operate in a more abstract realm when using thermodynamical representations. However, all approaches agree that any positive synergy will produce a more efficient system, up to the point of *maximum power.* A principle stating that "(…) systems prevail that develop designs that maximize the flow of useful energy" (Tilley, 2004, p. 121). A state that denotes the optimal function of many systems – especially ecological ones. Synergy effects can in this perspective be seen as the *means* with we attempt to optimize technological-ecological systems. And not only their efficiency. A high level of synergy will simultaneously give some indication of the effectiveness of a green technology system, in terms of the ability to co-exist symbiotically with ecological systems.

Ecological economics is suitable for assessing specific energy-interactions to a high level of detail. But the effectiveness might still escape this strategy of energy-accounting—which also turned out to be the Achilles heel of ecological economics. The attempt of representing the entire world by qualitatively different types of thermodynamic 'joules' has culminated in an endless mathematical endeavor of calculating myriads of energy states for different systems. Attempting to include all relevant interconnections and every non-linear behavior of natural systems. Recent literature has commented that "(…) to achieve its original vision ecological economics must return to its biophysical roots." (Melgar-Melgar & Hall, 2020, p. 1). We consider our more hands-on physical synergy-approach to connect more directly to such biophysical roots.

Our approach might not be suitable for developing a new economy, which is the purpose of ecological ecology and demands an extreme resolution for the processes described. But we consider it a sensible route towards sustainability assessment of technology systems.

9. References

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