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Moral impact of technologies from a pluralist perspective: Artificial photosynthesis as a case in point

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ABSTRACT

We propose and illustrate a model for evaluating the moral impact of technologies from a pluralist perspective. We conceptualize technological artefacts as having *moral profiles* that consist of the values served and disserved along five levels of decision-making: (1) problem, (2) strategy, (3) resources, (4) product and (5) design. The notion of complex equality, directly stemming from the pluralist philosophy of Michael Walzer, can function as a heuristic principle to guide the identification and analysis of imbalances along these five levels. We provide an illustrative case study of the moral profile of artificial photosynthesis (AP), an emerging technology for renewable fuel production that promises to resolve our current dependence on fossil fuels. We conclude by providing future directions for the implementation of pluralist ideas in R&D policy and in societal discourse on emerging and incumbent technologies.

1. Introduction

How must we choose between technologies that compete as solutions to a recognized problem? This question reveals surprising difficulties when we consider that technologies "have politics", to use the adage popularized by Winner [1], meaning that the moral impact of a technology always consists of both moral *gain,* in that the technology serves some values, and moral *residue,* in that the technology disserves other values [2–4]. Although technologies come into being as moral choices, in some cases the decision is quite straightforward because the moral gain clearly outweighs the moral residue (or vice versa). For example, the smallpox vaccine brought an invaluable moral gain by eradicating a devastating infectious disease on a global scale. By contrast, the gasoline additive known as TEL (tetraethyl lead), while effective as an anti-knock agent, brought about calamitous environmental problems that are still with us today. But such easy choices are rarities. Much more common is the situation where a technology's moral gain and its moral residue are more equally balanced. For example, many technologies compete nowadays as solutions to eliminate our dependence on fossil fuels by using renewable energy. Technologies such as wind turbines, solar panels, nuclear reactors (using either fusion or fission), water dams, biomass reactors, electrolyzers and geothermal plants have mixed moral consequences in that they comprise both moral gain and moral residue. None of these technologies obviously eliminates the others. The question of reasonable choice, particularly in what concerns R&D resources, is as urgent as it is challenging.

We want to contend that the philosophy of *value pluralism* [5–7] can provide a conceptual background for tackling issues of distributive justice in contexts where a plurality of technologies compete for resources as solutions to a designated problem. In particular, we argue that the pluralist concept of *complex equality* [8] can function as a heuristic principle for these issues, especially in highly competitive fields such as the energy sector.

On a disciplinary level, our contribution seeks to illustrate the potential of a cross-fertilization between moral and political philosophy on the one hand and the normative study of technology on the other. Pluralist ideas, have seldom been implemented in the context of technology development, even though the potential of such a move has been indicated sporadically in past studies [4,9,10]. The present study seeks to provide the building blocks for a normative approach to technological impact that goes beyond the separate evaluation of moral impact resulting from technology use and takes into consideration the entire

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chain of decisions that generate moral gain and moral residue along the way leading from the problem to the design. Our underlying ontological assumption is that technologies embody moral ideals – that each technology wears a certain image of the good life on its sleeve and encounters competing images of the good life as these are embodied in other existing or emerging technologies [11]. The analyst's goal is not to decide which image is to be preferred – it is to provide tools for seeing and understanding these competing images, their relationships, and their consequences.

Our paper is organized as follows. In Section 2 we introduce the philosophy of pluralism and the heuristic principle of complex equality. In Section 3 we turn to the application of this principle through a five-fold distinction between levels that constitute what we refer to as a *moral profile*. In Section 4 we exemplify this analysis by examining the emerging technology of artificial photosynthesis in relationship to competing technologies. In this case study we identify values served (moral gain) and values disserved (moral residue) at each of the five levels to the extent this is possible at the current state of the innovation process. Finally, in Section 5 we explain how pluralism and the principle of complex equality could be employed not only in the evaluation of technologies but also in the formulation of pluralist technological policies and governance frameworks.

2. Pluralism and the heuristic principle of complex equality

Value pluralism is a strand of moral and political philosophy that takes as a starting point the claim that our moral universe is populated by a wide variety of values (freedom, equality, love, justice, life, mercy, citizenship, integrity, safety, sustainability etc.) and that these values combine in various ways to form what individuals see as "choiceworthy ways of life" [12,13]. An agent's values "consist in those principles and ends which [s]he – in a cool, and non-self-deceptive moment – articulates as definitive of the good, fulfilling and defensible life" [14]: 215. From this perspective, moral choices are seen as the act of preferring some values over others, a preference that is further embodied in the artefacts we create through those choices [6,7,15].

The values that populate our moral universe are not only different in their social consequences and the associated modes of just distribution, but they are also *incommensurable* in that there is no fundamental value or principle to which they can all be reduced. There is no Archimedean point from which to resolve all moral conflict between values. There is no "view from nowhere" that we can always take in order to manage difficult choices [16]. It is true that problem-situations involve a lower threshold of what counts as a 'solution to the problem': once the milk is spilt the range of possible solutions undergoes a first reduction. This can be seen as a functional Archimedean point, an initial test of effectiveness, from which stakeholders can prima facie decide what counts as a potential solution. But the objectiveness of such a stance is illusory since both recognizing something as a problem and a set of acts as a solution to that problem are value-based and only objective from the perspective of participants who have assumed and internalized the relevant values under that definition and operationalization. Such a objectivization is then "reinforced by the fact that the critics of a practice [those rejecting something as a solution] take an observer's position with respect to it [the solution] but remain participants of the practice that provides them with their objections" [17]: 22). Taking the dog out for a walk is not prima facie a solution to the milk being spilt – and there is a sense in which it *objectively isn't* given a standard set of expectations and worries regarding hygiene around the house. But if the biggest danger is that of a panic attack, then leaving things as they are and going for a walk can start to be seen as a solution and even the optimal one.

What remains to be done? Isaiah Berlin, one of the founding figures of value pluralism, has aptly summarized the approach as follows:

> [W]e must engage in what are called trade-offs – rules, values, principles must yield to each other in varying degrees in specific situations. Utilitarian solutions are sometimes wrong, but, I suspect, more often beneficent. The best that can be done, as a general rule, is to maintain a precarious equilibrium that will prevent the occurrence of desperate situations, of intolerable choices – that is the first requirement for a decent society; one that we can always strive for, in the light of the limited range of our knowledge, and even of our imperfect understanding of individuals and societies. A certain humility in these matters is very necessary [5]: 17)

The quote shows that, in terms of their moral attitude, pluralists stand somewhere between relativists and rationalists: unlike relativists, they accept the idea of rational action and that some decisions are better than others; unlike rationalists, they accept the impact of historically situated beliefs that undermine the possibility of finding a universal method or principle for resolving all our conflicts [15]: 38–46). All this does not mean that with every decision we must serve all values equally. Indeed, given the above-mentioned incommensurability, one would be at pains to give substance to the notion of "serving all values equally" even if such a project were deemed advisable. Rather, from the middle ground between relativism and rationalism, pluralists insist on the need to maintain a moral equilibrium between various ideals that animate our moral choices and avoid the extreme dominance of some values over others. Decision strategies and policies should thus strive to maintain the "precarious equilibrium" mentioned by Berlin in the quote above. This idea has led to the notion of *complex equality*.

First developed by Michael Walzer [8] and subsequently applied in a variety of contexts [18–23], the notion of complex equality can best be understood in relationship to the more primitive notion of 'simple' equality. If we look to achieve simple equality within a community of individuals competing for scarce resources, we will direct our decisions towards the goal of creating and maintaining an equal distribution of those resources such that, ideally, nobody has more than anybody else. The problem with simple equality is that in practice it turns out to be completely unrealizable [8,22,23]: 18). The attempt to always keep gains and losses equal along all decision points and between all individuals is futile and, perhaps more importantly, it does not admit of the possibility that individuals might not prefer the same value combinations. One might sacrifice some wealth for some extra liberty, the other might sacrifice some liberty for some extra wealth. It is not at all clear that such trade-offs can be decided in advance. In contrast to simple equality, complex equality means striving not for an equal distribution of value but only the avoidance of *systematic dominance* of some value(s) over others across multiple decision points. Inequality, i.e., unequal distribution of values, is just so long as success in one sphere (say, wealth) does not translate into success in other spheres (say, political power). These unjust translations are sometimes referred to as "blocked exchanges", i.e., the situation where a value becomes so dominant in a system that it functions like a currency, buying off other values and disregarding these values' social meaning in the process [24–26]. Walzer calls this systematic dominance a form of *tyranny* and defines it, along philosophical lines that go back to Blaise Pascal, as the wish to obtain by one means what can only be properly obtained by another (1983: 17). To conclude, complex equality can be described as the state where a multitude of smaller inequalities cancel each other out without any one value systematically dominating the landscape.

What does it mean to employ complex equality as a heuristic principle in the evaluation of technological impact? This question has yet to be approached in the normative study of technology, within field such as ethics of technology, philosophy of technology or responsible innovation. The application of pluralist ideas to these fields, either in the context of research or that of policy, is still in its infancy. The more common ethical approaches tend to side-step questions of distributive justice, either evaluating technologies individually in terms of their specific risk and benefits [27] or focusing on the process of technological development and ensuring that this process is in accordance with principles of responsibility [28]. Both these approaches are of course very valuable, but they lack the apparatus to see technologies as part of a competition with other technologies and to understand what is needed to maintain an equilibrium between these alternatives. There is a growing need therefore to understand how we can evaluate technology not only based on its impact on society but also based on its impact on values – the value trade-offs that the technology instantiates and the tyrannies it might perpetuate. We suspect that such a turn can best be achieved by working under the methodological assumption that technologies, and technological artefacts by extension, are embodied moral choices between values, choices that promote one image of the good life while demoting others. This means seeing each technology as embodying a social contract by means of which some values are served more than others [11].

We propose that applying a heuristic principle of complex equality should begin with an understanding of what we will call the *moral profile* of a technology and its competitors. A moral profile is an overview of how a certain technology impacts our moral universe, the values it serves and those it ignores or disserves, all this in relationship to alternative technologies that have their own moral profile. This step will be further operationalized in Section 3 and its application will be illustrated by means of a case study in Section 4.

The analysis of technologies in terms of their moral profiles should be seen as a first step towards preventing systematic dominance and thus avoiding those impossible choices mentioned by Berlin to in the quote given above. It implies the need to maintain the constant and productive possibility of discussion and even agonism between alternative technologies [29,30]. The history of failed miracle solutions such as tetraethyl lead, asbestos and DDT suggests that a healthy suspicion for silver bullets, jackpots, and holy grails might also be necessary [31–36]. Maintaining agonism is thus a means of maintaining complex equality.

By way of concluding this section, let us note that the principle of complex equality can be used both retroactively in evaluating existing technologies and proactively in devising technological policy. Used proactively, complex equality is a policymaker's reminder that justice in distributing limited resources might involve weighing of alternative moral profiles, thinking in terms of lost chances and what economists call "opportunity cost" [37]. The general tendency of governments and research institutions is to focus on optimizing a 'winning' technology in the hope of driving down the costs and securing investments rather than maintaining an equilibrium between various efforts directed at the same problem [38,39]. Of course, exceptional situations can require tremendous focus and 'loyalty' for one technological solution to the neglect of others. Path dependency is not inherently a negative feature of a socio-technical system [40]. For example, the recent development of the (m)RNA vaccine against COVID-19 is an example of such an exceptional situation. More common however is the situation where various groups develop technological solutions gradually and in parallel each seeking to capitalize on values that are not served by its competitors. This dynamic can be observed in the energy sector where none of the incumbent technologies has managed to solve the problem of replacing fossil fuels and singlehandedly drive socio-technical change [41,42]. It is precisely because of such differences in context that we insist on the principle of complex equality being a heuristic rather than an unbending moral axiom – it is also why in the quote above Berlin speaks of the maintaining of equilibrium as a "general rule" rather than a universal one.

3. The moral profile of technologies

In this section we introduce and operationalize the concept of *moral profile of a technology*. We begin by reiterating the idea introduced above, that technological artefacts "have politics" in that they result from a complex and value-driven decisional process. This process creates moral gains and moral residue along the way giving rise to the following analytical question: How can we best represent this complex decisional process and the moral consequences (gains and residues) created along the way? The analyst must of course do justice to its complexity but at the same time it would be impractical and unnecessary to focus on every decision point and inquire into its moral consequences. Our approach is meant to complement the evaluation of technological artefacts as it is traditionally done in fields such as risk assessment [43], technology assessment [44] or ethics of technology and engineering [27], where the evaluation is typically focused on the desirable or undesirable moral consequences resulting from using the technological artefact, bracketing the many forms of gains and residues created in the "developmental context", i.e., in arriving at that technology designed in that way. Numerous methodologies have been developed in this way as instruments to investigate whether a certain *given* technology creates an acceptable balance of risks and benefits [45–49]. We insist therefore that a technology's impact should be evaluated based on the full picture of morally relevant decision nodes from the initial recognition of a problem to the specific design of a solution.

In what follows we make a distinction between five levels – or "decision nodes" – that have a moral impact and are therefore worth investigating in terms of values served and values disserved. The tradition of distinguishing between stages in the process of technological innovation is as old as the discipline of innovation studies itself and it is hard to find an approach that does not implicitly or explicitly cut the innovation pie one way or the other (for a comprehensive overview, see Ref. [50,116]. Whether it is seen as a linear process or as a socio-technical (systemic) change, the innovation process is typically modeled as a process unfolding over time, encountering barriers and opportunities along the way. This serves the purpose of understanding how best to improve or accelerate the innovation process or on the contrary control or decelerate it. But for evaluating the moral impact of technologies, we believe it is more practical to focus on the relevant choices embodied in a certain technology *together with alternatives left behind*. As we will show, conceptualizing technology as embodied moral decisions can be done independently of the problem-solving efforts behind each decision and, it is worth underlining, independently of the psychological processes of the stakeholders involved in the process.

At a first level, the recognition and prioritization of a *problem* has moral consequences because a status quo can only be evaluated as problematic relative to one or more values that are considered insufficiently served. The same status quo must simultaneously be evaluated as good, or satisfactory, in light of other value or values that are deemed (sufficiently) served. Poverty is of course an urgent global problem, but so is climate change, cancer, war, discrimination, drug use and many more. Both the decision to recognize the selected problem as a problem and the decision to prioritize it relative to others are morally consequential in that some values, and not others, are brought to the fore. Such issues are widely recognized for example in the study of global technological policies and the difficult choice between different sustainable development goals [51].

Second, once the problem has been selected, the *strategy* for tackling the problem will also bring about moral consequences. One might choose, e.g., the strategy of prohibiting (restricting) the behavior connected to the problem, but one might alternatively choose to incentivize an alternative form of behavior. If needed, further distinctions could be made between the same strategy applied in different ways, as when, e.g., the same strategy is pursued in either a radical fashion or through piecemeal adjustments. In all these cases, the problem stays the same but strategic choices have their own moral consequences. For example, the strategy of prohibition may result in a partial loss of individual freedom while the strategy of incentivizing, while maintaining individual freedom, may result in a slower change of the undesirable behavior.

Third, implementations of a chosen strategy will differ in terms of the *resources* they require. We can include here natural resources, human resources, financial resources, time, information, beneficial policy, infrastructure and community support. The choice of resources is relevant for the present analysis not only in that the use of these resources is deemed just, responsible, efficient and so forth but it implies that the resources are sufficiently available in that configuration. These dimensions are both morally consequential. For example, in the field of mobility we might compare electric vehicles and electric trains as differing most saliently in the infrastructure they require while at the same time compare electric vehicles and fuel-cell vehicles as differing most saliently in the natural resource they require. The collection and use of resources a certain configuration implies a prioritization of values (and de-prioritization of other values) so that understanding the full moral profile of a technology must duly take this prioritization process into account.

Fourth, once a certain strategy and resource configuration is accepted, choosing between different *products* that can solve the same issue will be morally consequential. For example, having decided to use electricity stored in lithium-ion batteries to replace fossil-fuels in the realm of personal mobility, we still must choose whether this is achieved with electric bikes, electric scooters, electric skateboards, electric unicycles etc. These will be different products fueled at a fundamental level by the same natural resource and will thereby have different consequences for the stakeholders involved in terms of safety, functionality, reliability etc. It goes without saying that products resulting from the same configuration of resources can also compete with products resulting from other configurations of resources as when electric cars compete with fuel-cell cars or electric bikes compete with normal bikes.

At a fifth and final level we include the moral implications of *design*. The notion of 'design' is nowadays employed in a broad sense to include various decisions that would fall under different levels under the categorization proposed here. Every technological artefact is then seen as wearing its moral profile on its sleeve, so to speak, such that the moral issues settled along the way in the previous four levels can be reconstructed in the product's design features [52,53]. But a reductionist move of this type is not needed here – not everything boils down to aspects of design or should be reconstructed starting from aspects of design. By "design" we simply mean the last level of product development, the many ways in which the same product (and implicitly the same resources) could be used to customize the product's effects on its users and is use environment.

Each of the five levels presented is characterized by a prototypical question that can be used to guide the analysis at that level. Depending on the answer to that question, some values will be prioritized and will appear on the left box while others will be de-prioritized and will appear on the right box. Fig. 1 is a visual representation of the decision tree from problem to design and the resulting moral impact (values prioritized and de-prioritized). Before we illustrate our approach, two methodological observations are in order.

First, we note that the relationship between a technology and its impacted values is not a discoverable fact but an analytical claim that is heavily dependent on one's chosen method of analysis. As proposed, our model is compatible with various analytical methods for understanding the relationship between technologies and value from the more basic ethics-of-technology approaches [27], impact assessment [54] or multi-criteria decision analysis [55,56] to the more complex ones in which the relationship between a technology and our moral universe is assumed to be dynamic due to bilateral changes on both the technology and the value side [57,58]. There are many important differences between these approaches, yet we should not assume that there is no common ground. They all assume that values constitute a correct analytical stance from which to investigate our relationship with technologies and socio-technical systems in general. At the same time, it is common knowledge that values are fuzzy things. Working with them is not an exact science and they are sometimes complex enough such that one and the same technology can serve a certain value and disserve it at the same time. For example, electric bicycles serve environmental values by replacing fossil-fuel cars and scooters and disserve these values by replacing conventional (non-electric) bikes. Given this fuzziness and complexity, an overly precise rendition of the technology-value relationship in quantitative terms, is neither obligatory nor particularly useful at the time it can be acquired. This is the fundamental insight of the Collingridge dilemma: when moral impacts becomes so evident that it can be quantified, intervening in the socio-technical system is already costly and difficult [59].

A second methodological note concerns the notion of 'alternatives' employed here. Distinguishing between alternatives is also heavily dependent on one's analytical starting points. For example, there are various ways to distinguish between strategies and none of these will be universally applicable. In the policy literature, we find the familiar distinctions between different policy responses to a problem-situation, namely prohibition, innovation, deregulation, incentivizing etc. [60, 61]. However one might operate with different distinctions if one is interested in, say, the trade-off between growth strategies and degrowth

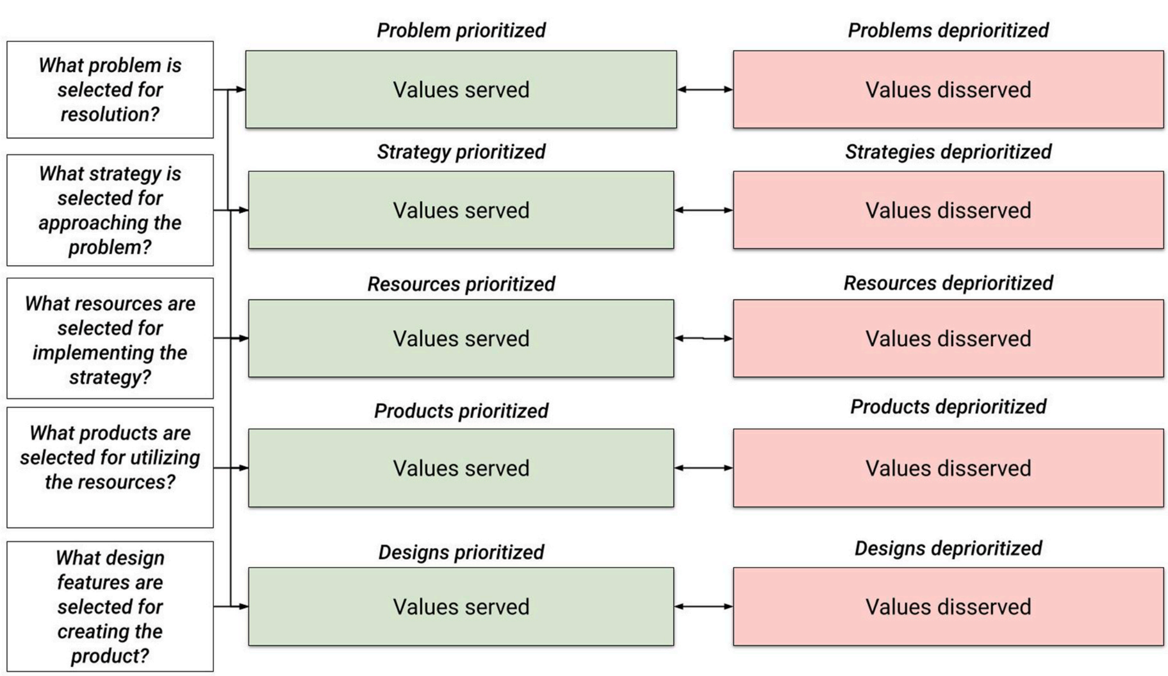

Fig. 1. The moral profile of a technology consisting of five levels at which choice creates moral gain and moral residue.

strategies [62], open or closed innovation strategies [63] or the Popperian trade-off between utopian social engineering and piecemeal social engineering [64]. Our attitude regarding this diversity is the same as above – we welcome it and insist that the model proposed here seeks to be compatible with different methodological options. In fact, from a pluralist standpoint we are almost compelled to advise students to be very conscious of the context-dependency of their methodological choices when it comes to analyses of the kind proposed here while being quite resolute about the need to undertake such evaluations even in a context of information paucity. The goal of the analysis is to understand value trade-offs at different levels of technological decision-making. This goal, we believe, must be compatible with different methodological toolkits.

4. Case in point: A moral profile for artificial photosynthesis

Artificial photosynthesis (AP, henceforth) refers to the process of producing fuels from carbon dioxide (CO_2) using sunlight and water (H_2O). The storing of solar energy into chemical bonds is often referred to as the 'Holy Grail' of modern science [65–67]. If it can be done cost-effectively, the technology can eliminate or at least significantly alleviate our global dependence of fossil fuels. The term 'artificial photosynthesis' is relatively recent and is being employed still with some semantic variation. In the widest sense, AP can be used to refer to any solar-driven reaction such as using solar-generated electricity for splitting water into oxygen and hydrogen. More commonly the term is employed in a narrower sense to refer exclusively to systems that, mimicking the process of natural photosynthesis, use solar energy to convert CO_2 into useable fuels such as methane (CH_4) or ethanol (C_2H_5OH). Current research on AP consists of experimenting with various materials in order to understand the material and design conditions of the photosynthetic process and to find a cost-effective configuration for producing fuels in this way [68,69]. For the past several decades, many configurations have been proposed and tested in this way [70–72]. Although AP is still an emerging technology, its innovation path is sufficiently clear to undertake an initial analysis of its technology's moral profile according to the model introduced in the previous section. We therefore start with the first question: What problem is selected for resolution?

The main driver behind researching AP is the global reduction of fossil fuel use (e.g., [69,71,73–75]. The hope is that, given the right materials in the right configuration, we can harvest solar energy to produce fuels that are functionally similar to fossil fuels in that they serve the same purposes for a comparable price. Reducing dependence on fossil fuels is morally desirable in view of both individual values (increased quality of life) and environmental ones (climate preservation, decreased pollution), but it also constitute an increase in freedom by disrupting our dependence on fossil-fuel states and companies. Furthermore, since solar energy is relatively equally dispersed around the globe, a decentralized energy system based on locally produced solar fuels can also serve values such as equality through a reduction of energy poverty [76].

Nevertheless, although fossil fuel dependence is surely a "grand challenge" [77], directing resources towards its resolution implies deprioritizing other equally grand challenges and thus disserving the values connected to those challenges. For example, solar fuels are not, except perhaps incidentally, connected to problems such as unemployment, food insecurity, digital divide, pandemic diseases, oppression of minorities and others. Solar fuels do not contribute to the resolution of these problems for the obvious reason that they are not problems that solar fuels can solve. But we must nonetheless keep in sight that the prioritization of climate challenges involves the deprioritization of others and that systematic dominance can occur at this level.

At the second level of analysis, we inquire into the selected strategy for tackling the problem of fossil fuel dependence. AP can be said to represent a *technological* strategy since it constitutes a technological response to the problem. By contrast, a *regulatory* strategy consists of the development and implementation of new legislation that would restrict the use of fossil fuels, while an *economic* strategy consists of managing and shaping economic conditions for the production and consumption of fossil fuels. The identified problem is of course complex enough to allow for (and perhaps require) a combination of these strategies, but we are interested, as above, in the choice of developing technology as distinct from the others. What is the value trade-off in this case? Sustainable technologies such as AP, if successful, can allow us to maintain our current levels of energy consumption and even accommodate new energy users from developing countries currently in the process of industrialization [71,78]. If a technology like AP can fix the problem of energy *origin*, swapping fossil energy for solar energy, then our current use of energy can be maintained. This would serve individual values (freedom to use energy-intensive technologies, personal comfort, access to technological benefits) as well as political ones (minimal state intrusion, conservation of status quo). These values are typically associated with what is known as a *technological fix* [79] and the *moral obligation to innovate* in response to grand challenges [4]. The other strategies would surely be more intrusive on individual liberty since they would curb the use of energy-intensive technologies, but they could be more effective and less expensive. This was recently illustrated by the drastic and immediate reduction of CO_2 emissions during the coronavirus pandemic in 2021 after air-travel was forbidden by governments worldwide [80]. Impressive as these positive environmental effects may be, it is arguably only in the extraordinary context of a pandemic that such drastic prohibitions can be implemented. In choosing the technological fix, we most saliently choose more freedom over less impressive environmental results.

At the resource level, AP uses the solar energy (the energy that irradiates from the Sun). In this it can be contrasted with windmills that use aeolian energy, nuclear plants that use nuclear energy, river dams that use hydropower and others. The case for each resource depends on the specific conditions for harvesting and storing that energy. But although all these resources can lead to positive environmental effects, solar energy is the only one that is globally and fairly uniformly available across the earth. The promise encapsulated in AP is that of offering something like a global solution to the dependence on fossil fuels conceived as a "Terawatt Challenge", the challenge of producing sustainable fuels at a terawatt level, not just national or local sustainability goals. This is why AP is sometimes referred to as the "Holy Grail" of chemistry [65,78,81–84]. However, global solutions might be slow solutions. Aeolian and nuclear energy might be serving environmental values better in the short run since they are already available and contributing to the energy transition. Furthermore, it is every country's geopolitical right to exploit those resources to which it has access. Thus, with many similarities between the resources involved, the most salient trade-off is that between long-term efficiency and equality (a global solution to a global problem) and short-term efficiency and political rights (local solutions based on state resources).

At the fourth level of analysis, the main question regards the product that is being created through the exploitation of the selected resource (solar energy). At this level we can make a broad distinction between electricity and fuel, i.e., between *solar-to-power* technologies that harvest solar energy and turn it into an electric current and *solar-to-fuels* technologies that harvest the same solar energy and store it in the chemical bonds of fuels such as hydrogen and methane. AP belongs to the second category since it converts solar energy into fuels. What is the trade-off between creating electricity and creating molecules? Solar-to-power technologies are significantly more advanced and are currently upscaled globally in the form of photovoltaic (PV) panels. But the technology suffers from low efficiency [85,86] and intermittence [87,88]. Additionally, they require rare metals and other materials with a high CO_2 footprint [89] and are connected to uncertain waste management practices [90,91]. The drawbacks of solar-to-fuel technologies suffer are unclear and will most probably depend on the materials employed for reducing CO_2 in the creation of fuels. Compared to present solar-to-power technologies, AP will plausibly have to deal with mass transport of reactants and products and, at least in the initial stages, the same need for rare or precious materials [70,92]. This will affect not only environmental values because of reduced efficiency but will make the technology more difficult to scale to developing countries. Yet offsetting these drawbacks is the fact that solar fuels are simultaneously a solution for harvesting and storing solar energy, whereas solar electricity requires separate technologies for storage such as batteries or electrolyzers that bring their own moral profile into the equation [74]. Concluding, the trade-off at the product level is that between solar electricity, a well-known product that works on a small-scale but has potential disadvantages threatening its scalability in the future, and solar fuels, a product that we do *not* know how to make yet and has potential advantages and scalability benefits. Solar electricity is the sub-optimal but cautious choice; solar fuels are risky but potentially optimal. As AP develops further, a deeper analysis of the resource level can be undertaken that takes into consideration not only the primary resource (solar energy) but also the other resources that are needed for the technology to work. Particularly in the context of a global scarcity of noble metals, it crucial to compare AP devices in terms of their components. A device that uses copper or some other abundant metal as an electrode will have a different moral impact, because of its applicability and scalability, from the same device using platinum and both will be different from another AP device that does not use an electrode at all.

The fifth and final level concerns the design of AP technologies. The idea of making an artificial leaf by replicating the sunlight-driven fuel production processes found in plants was first formulated in the early 20th century [93] and has been a the topic of intense and quite diverse research efforts ever since [71,94]. At present, due the immense complexity of the natural photosynthetic process and the many designs through which it can be mimicked, the term 'artificial photosynthesis' has come to refer to very different designs. A standard typology employed to make sense of these differences is that between *homogeneous* systems in which the catalyst and reactants are in the same phase, usually liquid or gas [95] and *heterogeneous* systems in which the catalyst and reactants are in different phases, the catalyst typically being solid and the reactants liquid or gaseous [96,97]. However, recent developments have generated hybrid homogeneous-heterogeneous systems [98]. The distinction between homogeneous and heterogeneous systems is widely employed among researchers in AP and it successfully captures a fundamental distinction in the basics of how the artificial leaf is supposed to look like (see, e.g., [70,92,99]. However, the distinction is not necessarily the most revealing for understanding moral impact of AP designs. A more meaningful distinction for our purposes would be that between *conservative* designs that rely on electricity to some degree to drive the chemical reactions and *disruptive* designs that seek to move away completely from the concept of using electrical current to drive the chemical reactions. Recent analyses have argued that the essential trade-off between these two categories of design is one between the deployability of the conservative designs given their higher level of technology readiness and the scalability of the disruptive designs given to their avoidance of complications arising from the use of electrical current [100–102]. In terms of environmental values the trade-off is similar to the ones we have seen in the previous level: small-scale environmental benefits now, versus larger-scale environmental benefits later. But quite separately from the impact on environmental values, it has been argued for instance that a scalable technology for decentralized energy production can lead to a more just energy system by ameliorating socio-economic differences between individuals and, if we factor in the quality of the energy grid, between countries [103–105]. Scalability is thus not only impacting environmental values through a greater replacement of fossil fuels but also political values through the disruption of current path dependencies in our energy systems.

Let us take stock. As an emerging technology, AP can be seen as embodying moral choices on five levels: the choice of a certain challenge (dependence on fossil fuels), the choice of a strategy for tackling that challenge (new technology for alternative fuels), the choice of a primary resource (solar energy), the choice of a primary output (useable fuels), and the choice of a certain technological design (conservative and disruptive designs). These choices and the discussed values are illustrated in Fig. 2 below.

Since none of these choices are self-evidently superior to their alternatives, evaluation can proceed along the lines proposed here by understanding the primary trade-off in each case and discovering early imbalances in complex equality. We have seen for instance that the current choices for tackling the fossil-fuel problem constitute a systematic favoring of *electricity* at levels 3–5, whether this electricity is used as such or stored in various ways. This has its justification that can be formulated in terms of values served: it serves environmental values (reduced atmospheric CO_2), political ones (conservation of status quo and individual freedom) and individual values (improved quality of life). However, researchers are seeing the limitations arising from the use of electricity such as the need for rare materials and powerful infrastructures or the low efficiencies as serious barriers downstream. We hear in their critique of incumbent technologies the Berlinian warning against "desperate situations" where moving forward involves critical moral dilemmas. The energy of the future, they insist, needs to be "fast-food energy", in that it must be cheap, decentralized and easily accessible, but the current energy systems are not moving in that direction [106]. The technology of AP can balance these choices constantly favoring the development path through electricity but only in some of their more revolutionary designs. However, we have seen that AP is generally seen as a "holy grail", an improbable solution that does not constitute the focus of current governmental and EU-level funding schemes that focus, as seen on levels 2–4, on already-existing, commercial solutions.

5. Conclusion: towards pluralism in policy and discourse

The political philosophy of pluralism constituted the starting point of our inquiry [6,7,15]. The two main ideas that we extracted from this philosophy were, first, that moral gain (values served) is always accompanied by some degree of moral residue (values disserved) and, second, that since values are plural and incommensurable, it is responsibility in the development of technology to take the form of finding a "precarious equilibrium" between values and the timely anticipation of "desperate situations" where we maneuver the socio-technical system towards moral dilemmas in which any choice results in drastic violation of one or more values. We then argued that the principle of complex equality as developed by Walzer among others can be employed as a heuristic device for anticipating possible forms of value tyrannies that are prone to generate moral dilemmas. A novel proposal relative to standard approaches to moral evaluation of technology, we argued that this principle must be followed not only when it comes to a technology's design but at five levels of decision-making: the choice of problem to be solved by the technology, the choice of strategy, the choice of resources, the choice of product and finally the choice of design. Using this approach, a technology will appear as the embodiment of a complex decision tree with values being served and disserved at each of the five levels. For illustrative purposes, we carried out this exercise with respect to artificial photosynthesis, an emerging technology for producing sustainable fuels by using solar energy.

The principle of complex equality can be employed not only as a tool for the ethical evaluation of technologies but also as a guiding principle in policymaking. The most obvious realm of application is that of pubic *R&D* funding, where the inevitability of moral residue would offer resources for arguing against the diminishing of technological diversity. Since R&D programs aim for efficiency in spending public funds and the most efficient technologies are typically the ones that have the highest level of technology readiness, R&D funding will always tend to favor winners [107]. Particularly in the field of energy public spending in the

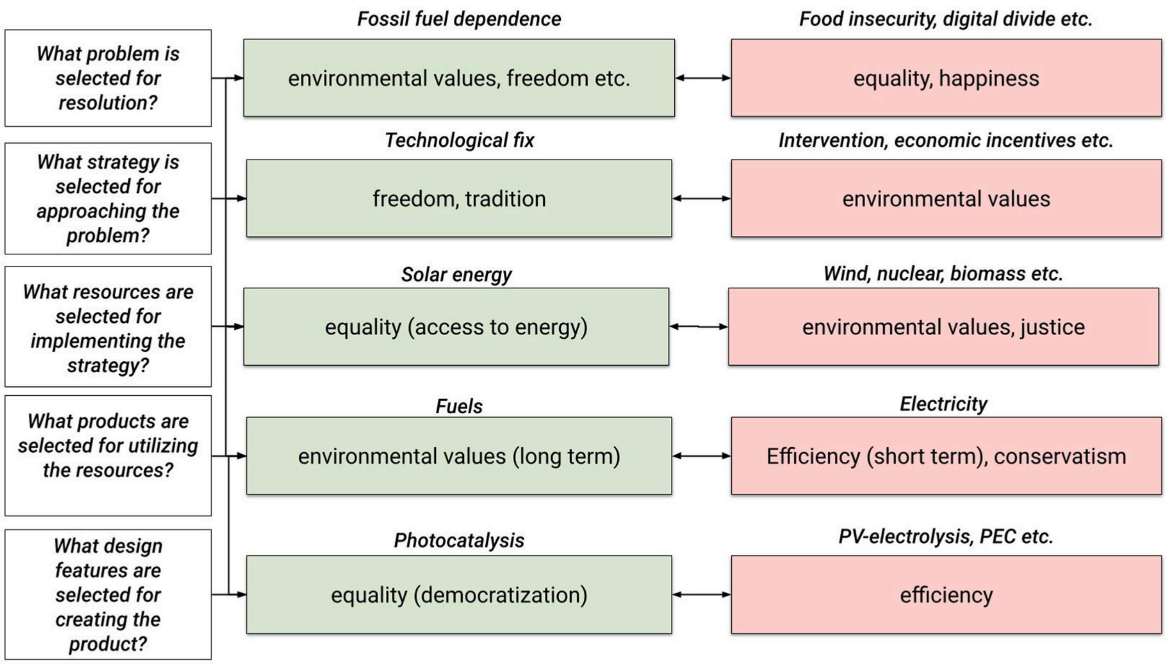

Fig. 2. Moral profile of Artificial Photosynthesis.

past 30 years has consistently shown an uneven pattern of spending that favors incumbent technologies for climate-change mitigation and disfavors underdeveloped, emerging and disruptive technologies [108]. Photovoltaic panels are prime examples in this sense. As established technologies functioning close to their optimum energy efficiency, photovoltaic panels have received sustained financial and policy support in the past decades quite independently of warnings regarding their scalability [109,110], recycling [111] and scarcity of critical minerals [112]. A funding policy driven by complex equality would seek to offer a broader spectrum of financial and policy support to technologies whose associated moral gains and residues cancel each other out.

In addition to its application in questions of technological policy, the principle of complex equality can also be applied in the analysis and evaluation of stakeholders' discourse on new technologies. With its traditional techno-scientific propensity, discourse on new technologies focuses on the problems that are solved, the nature and efficiency of the solution, and the associated costs. The principle of complex equality encourages us to unearth the moral impact of technologies early on in their development, to understand and deliberate on the trade-off being proposed. This could be done by identifying *discussion stoppers,* i.e., discursive and non-discursive strategies by means of which conflict is portrayed as resolved or obsolete [30] as well as *discussion starters,* i.e., discursive and non-discursive strategies by means of which a conflict that is generally believed to be resolved or obsolete is brought back on the public agenda. Furthermore, and should nowadays be quite uncontroversial, the inclusion of diverse stakeholders in science and technology is a useful though not infallible means for maintaining or reviving technological agonism [47,113,114]. The social sciences and the humanities have been particularly outspoken recently on the need for responsibility and inclusion in the relationship between technology and society, yet the moral vocabulary designated to handle the task of creating and understanding this new relationship is borrowed largely from moral philosophy where simple (sometimes imaginary) cases are discussed. This vocabulary is not designed to capture the subtleties and complexity of the multi-layered contract between society and technology. The analytical relationship between technological features such as efficiency, scalability, accessibility, and safety on the one hand our moral universe populated by values such as freedom, equality, and justice on the other. If pluralists are right in their fundamental worldview, the two sets are in a permanent interaction as technologies influence our moral universe and this universe, in turn, influences technological innovation.

Declaration of competing interest

The authors state that they have no existing conflict of interest.

Data availability

No data was used for the research described in the article.

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References

[1] L. Winner, Do artifacts have politics? in: D.M. Kaplan (Ed.), Readings in the Philosophy of Technology Rowman & Littlefield Publishers Lanham, Lanham, 2009.
[2] I. Van de Poel, Values in Engineering Design', *Philosophy of Technology and Engineering Sciences*, Elsevier, 2009, pp. 973–1006.
[3] I. van de Poel, Conflicting values in design for values, in: J. van den Hoven, P. E. Vermaas, I. van de Poel (Eds.), Handbook of Ethics, Values, and Technological Design: Sources, Theory, Values and Application Domains, Springer, 2014, pp. 1–23.
[4] J. Van den Hoven, G.-J. Lokhorst, I. van de Poel, Engineering and the problem of moral overload, Sci. Eng. Ethics 18 (2012) 143–155.
[5] I. Berlin, The Crooked Timber of Humanity: Chapters in the History of Ideas, Princeton University Press, Princeton, 2003.
[6] G. Crowder, The Problem of Value Pluralism: Isaiah Berlin and beyond, Routledge, New York, 2020.
[7] G. Crowder, Pluralism, Polity, Cambridge, UK ; Malden, MA, 2011, p. 186.
[8] M. Walzer, Spheres of Justice: a Defense of Pluralism and Equality, Basic Books) xviii, New York, 1983, p. 345.
[9] E.-M. Forsberg, Value pluralism and coherentist justification of ethical advice, J. Agric. Environ. Ethics 20 (1) (2007) 81–98.
[10] J. Ramirez, S. Böhm, For more pluralistic critiques of colonialism: a response to Dunlap, Energy Res. Social Sci. 82 (2021), 102303.
[11] E.O. Popa, The golem and the leviathan: two guiding images of irresponsible technology, Philos. Technol. 35 (4) (2022) 91.

[12] I. Berlin, in: Ian Harris (Ed.), Liberty : Incorporating Four Essays on Liberty, Oxford University Press, Oxford, 2002.
[13] I. Berlin, Against the Current, Princeton University Press, Princeton, 2013.
[14] G. Watson, Free agency, J. Philos. 72 (8) (1975) 205–220.
[15] J. Kekes, The Morality of Pluralism, Princeton University Press) xii, Princeton, N. J., 1993, p. 227.
[16] T. Nagel, The View from Nowhere, Oxford University Press) xi, New York, 1986, p. 244.
[17] P. Feyerabend, Science in a Free Society, NLB, London, 1978, p. 221.
[18] F. Arler, Global partnership, climate change and complex equality, Environ. Val. 10 (3) (2001) 301–329.
[19] C. Armstrong, Complex equality: beyond equality and difference, Fem. Theor. 3 (1) (2002) 67–82.
[20] R.J. Arneson, Against" complex equality, Publ. Aff. Q. 4 (2) (1990) 99–110.
[21] W.A. Galston, The Practice of Liberal Pluralism, Cambridge University Press) x, Cambridge, UK ; New York, 2005, p. 205.
[22] R. Lang, Complex Equality and the Court of Justice of the European Union: Reconciling Diversity and Harmonization, Brill, New York, 2018.
[23] D. Miller, Complex equality, in: D. Miller, M. Walzer (Eds.), Pluralism, Justice and Equality, Oxford University Press, Oxford, 1995, pp. 197–225.
[24] J. Andre, Blocked exchanges: a taxonomy, in: D. Miller, M. Walzer (Eds.), Pluralism, Justice and Equality, Oxford University Press, Oxford, 1995, pp. 171–197.
[25] T.R. Machan, Blocked exchanges revisited, J. Appl. Philos. 14 (3) (1997) 249–262.
[26] M.J. Sandel, The Tyranny of Merit : What's Become of the Common Good?, first ed., Farrar, Straus and Giroux, New York, 2020, p. 272.
[27] P. Brey, Ethics of emerging technology, in: S.O. Hansson (Ed.), The Ethics of Technology: Methods and Approaches, Rowman & Littlefield International), London ; New York, 2017, pp. 175–193.
[28] R. Owen, J. Stilgoe, P. Macnaghten, M. Gorman, E. Fisher, D.H. Guston, in: R. Owen, J. Bessant, M. Heintz (Eds.), A Framework for Responsible Innovation, Responsible Innovation, John Wiley & Sons, Ltd., London, UK, 2013, pp. 27–51.
[29] V. Blok, From participation to interruption: toward an ethic of stakeholder engagement, participation, and partnership in corporate social responsibility and responsible innovation, in: R. von Schomberg, J. Hankins (Eds.), International Handbook of Responsible Innovation, Edward Elgar, Celtenham, UK, 2019, pp. 243–259.
[30] E.O. Popa, V. Blok, R. Wesselink, An Agonistic Approach to Technological Conflict, Philosophy & Technology, 2020, pp. 1–21.
[31] H.M. Collins, T. Pinch, The Golem : what You Should Know about Science, second ed., Cambridge University Press) xix, Cambridge England ; New York, 1998, p. 192.
[32] H.M. Collins, T. Pinch, The Golem at Large: what You Should Know about Technology, Cambridge University Press, Publisher description, 2002.
[33] H.M. Collins, T. Pinch, Dr. Golem: How to Think about Medicine, University of Chicago Press, 2005.
[34] D. Gee (Ed.), *Late Lessons from Early Warnings: the Precautionary Principle 1896–2000* (Dennmark: EEA), 2001.
[35] P. Harremoës, D. Gee, M. MacGarvin, A. Stirling, J. Keys, B. Wynne, S. Vaz (Eds.), Late Lessons from Early Warnings: Science, Precaution, *Innovation*, vol. 1, European Environmental Agency, Copenhagen, 2013.
[36] T.P. Hughes, Networks of Power : Electrification in Western Society, 1880-1930, Johns Hopkins University Press) xi, Baltimore, 1983, p. 474.
[37] J. Buchanan, Cost and choice, in: C.K. Rowley, F. Schneider (Eds.), The Encyclopedia of Public Choice, Springer US), Boston, MA, 2004, pp. 454–456.
[38] S.J. Liebowitz, S.E. Margolis, Path dependence, lock-in, and history, J. Law Econ. Organ. 11 (1) (1995) 205–226.
[39] R.W. Rycroft, D.E. Kash, Path dependence in the innovation of complex technologies, Technol. Anal. Strat. Manag. 14 (1) (2002) 21–35.
[40] R. Garud, A. Kumaraswamy, P. Karnøe, Path dependence or path creation? J. Manag. Stud. 47 (4) (2010) 760–774.
[41] S. Jacobsson, A. Bergek, Transforming the energy sector: the evolution of technological systems in renewable energy technology, Ind. Corp. Change 13 (5) (2004) 815–849.
[42] G. Papachristos, Diversity in technology competition: the link between platforms and sociotechnical transitions, Renew. Sustain. Energy Rev. 73 (2017) 291–306.
[43] C.P. Kitsos, T.A. Oliveira, A. Rigas, S. Gulati (Eds.), Theory and Practice of Risk Assessment, Springer, New York, 2015.
[44] A. Grunwald, Technology Assessment: Concepts and Methods, vol. 9, Elsevier BV, 2009, p. 44.
[45] J. Burgess, J. Chilvers, Upping the ante: a conceptual framework for designing and evaluating participatory technology assessments, Sci. Publ. Pol. 33 (10) (2006) 713–728.
[46] M. Burget, E. Bardone, M. Pedaste, Definitions and conceptual dimensions of responsible research and innovation: a literature review, Sci. Eng. Ethics 23 (1) (2017) 1–19.
[47] J. Stilgoe, R. Owen, P. Macnaghten, Developing a framework for responsible innovation, Res. Pol. 42 (9) (2013) 1568–1580.
[48] J. Stilgoe, S.J. Lock, J. Wilsdon, Why should we promote public engagement with science? Publ. Understand. Sci. 23 (1) (2014) 4–15.
[49] J. Wilsdon, R. Willis, See-through Science: Why Public Engagement Needs to Move Upstream, Demos, London, 2004.
[50] M. Dodgson, D. Gann, A. Salter, The Management of Technological Innovation : Strategy and Practice, New edn., Oxford University Press) xxvii, Oxford ; New York, 2008, p. 373.
[51] E.B. Barbier, J.C. Burgess, 'Sustainable development goal indicators: analyzing trade-offs and complementarities', World Dev. 122 (2019) 295–305.
[52] B. Friedman, D. Hendry, Value Sensitive Design : Shaping Technology with Moral Imagination, The MIT Press) xxi, Cambridge, Massachusetts, 2019, p. 229.
[53] J. van den Hoven, Value sensitive design and responsible innovation, in: R. Owen, J. Bessant, M. Heintz (Eds.), Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society, WILEY & Sons,Ltd. , Publication), UK, 2013, pp. 75–83.
[54] L. Canter, Environmental impact assessment, in: McGraw-Hill Series in Water Resources and Environmental Engineering, second ed., McGraw-Hill) xx, New York, 1996, p. 660.
[55] M. Ehrgott, J. Figueira, S. Greco, *Trends in Multiple Criteria Decision Analysis* (International Series in Operations Research & Management Science, Springer) xvi, New York, 2010, p. 412.
[56] M. Ehrgott, J. Figueira, S. Greco, Multiple Criteria Decision Analysis : State of the Art Surveys, Springer) xxxvi, New York, 2005, p. 1045.
[57] M. Boenink, O. Kudina, Values in responsible research and innovation: from entities to practices, J. Responsible Innovat. 7 (3) (2020) 450–470.
[58] I. van de Poel, O. Kudina, Understanding technology-induced value change: a pragmatist proposal, Philos. Technol. 35 (2) (2022) 40.
[59] D. Collingridge, The Social Control of Technology, Frances Pinter, London, 1980.
[60] H.K. Colebatch, R. Hoppe, Handbook on Policy, Process and Governing, Edward Elgar Publishing Limited) xiv, Cheltenham, UK ; Northampton, MA, USA, 2018, p. 516.
[61] C.M. Weible, Theories of the Policy Process, fifth ed., Routledge, New York, NY, 2023 cm.
[62] G. D`Alisa, F. Demaria, G. Kallis, Degrowth: a Vocabulary for a New Era, 2014 (Routledge).
[63] H.W. Chesbrough, Open Innovation: the New Imperative for Creating and Profiting from Technology, Harvard Business Press, 2003.
[64] K.R. Popper, *The poverty of Historicism* (With Some Corrections, edn., Routledge & Paul, London, 1961, p. 166.
[65] A.J. Bard, M.A. Fox, Artificial photosynthesis: solar splitting of water to hydrogen and oxygen, Acc. Chem. Res. 28 (3) (1995) 141–145.
[66] M. Barroso, L.G. Arnaut, S.J. Formosinho, Proton-coupled electron transfer in natural and artificial photosynthesis, Proton-Coupled Electron Transfer: A Carrefour of Chemical Reactivity Traditions. RSC Catalysis Series (8) (2011) 126–151.
[67] G.W. Brudvig, S. Campagna, Introduction to a themed issue of Chemical Society Reviews on artificial photosynthesis, Chem. Soc. Rev. 46 (20) (2017) 6085–6087.
[68] C. Liu, B.C. Colón, M. Ziesack, P.A. Silver, D.G. Nocera, Water splitting–biosynthetic system with CO_2 reduction efficiencies exceeding photosynthesis, Science 352 (6290) (2016) 1210–1213.
[69] B. Zhang, L. Sun, Artificial photosynthesis: opportunities and challenges of molecular catalysts, Chem. Soc. Rev. 48 (7) (2019) 2216–2264.
[70] S. Ardo, D. Fernandez Rivas, M.A. Modestino, V. Schulze Greiving, F.F. Abdi, E. Alarcon Llado, V. Artero, K. Ayers, C. Battaglia, J.-P. Becker, D. Bederak, A. Berger, F. Buda, E. Chinello, B. Dam, V. Di Palma, T. Edvinsson, K. Fujii, H. Gardeniers, P. Westerik, Pathways to electrochemical solar-hydrogen technologies, Energy Environ. Sci. 11 (10) (2018) 2768–2783.
[71] D. Gust, 'An Illustrative History of Artificial Photosynthesis', Advances in Botanical Research, vol. 79, Elsevier, 2016, pp. 1–42.
[72] R.L. House, N.Y.M. Iha, R.L. Coppo, L. Alibabaei, B.D. Sherman, P. Kang, M. K. Brennaman, P.G. Hoertz, T.J. Meyer, Artificial photosynthesis: where are we now? Where can we go? J. Photochem. Photobiol. C Photochem. Rev. 25 (2015) 32–45.
[73] J. Barber, P.D. Tran, From natural to artificial photosynthesis, J. R. Soc. Interface 10 (81) (2013), 20120984.
[74] D. Gust, T. Moore, A. Moore, Solar fuels via artificial photosynthesis, Acc. Chem. Res. 42 (12) (2009) 1890–1898.
[75] N.S. Lewis, Developing a scalable artificial photosynthesis technology through nanomaterials by design, Nat. Nanotechnol. 11 (12) (2016) 1010–1019.
[76] M. González-Eguino, Energy poverty: an overview, Renew. Sustain. Energy Rev. 47 (2015) 377–385.
[77] D. Foray, D.C. Mowery, R.R. Nelson, Public R&D; and social challenges: what lessons from mission R&D; programs? Res. Pol. 41 (ARTICLE) (2012) 1697–1702.
[78] N. Abas, E. Kalair, A. Kalair, Q. al Hasan, N. Khan, Nature inspired artificial photosynthesis technologies for hydrogen production: barriers and challenges, Int. J. Hydrogen Energy 45 (41) (2020) 20787–20799.
[79] L. Rosner, The Technological Fix: How People Use Technology to Create and Solve Problems, Routledge, 2013.
[80] C. Le Quéré, R.B. Jackson, M.W. Jones, A.J. Smith, S. Abernethy, R.M. Andrew, A. J. De-Gol, D.R. Willis, Y. Shan, J.G. Canadell, Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement, Nat. Clim. Change 10 (7) (2020) 647–653.
[81] K. Brinkert, Energy Conversion in Natural and Artificial Photosynthesis, Springer, 2018.
[82] M. Đokić, H.S. Soo, Artificial photosynthesis by light absorption, charge separation, and multielectron catalysis, Chem. Commun. 54 (50) (2018) 6554–6572.
[83] G.-F. Luo, Y. Biniuri, W.-H. Chen, E. Neumann, M. Fadeev, H.-B. Marjault, A. Bedi, O. Gidron, R. Nechushtai, D. Stone, T. Happe, I. Willner, Artificial photosynthesis with electron acceptor/photosensitizer-aptamer conjugates, Nano Lett. 19 (9) (2019) 6621–6628.

[84] H.-L. Wu, X.-B. Li, C.-H. Tung, L.-Z. Wu, Recent advances in sensitized photocathodes: from molecular dyes to semiconducting quantum dots, Adv. Sci. 5 (4) (2018), 1700684.
[85] M. Jaszczur, A. Koshti, W. Nawrot, P. Sędor, An investigation of the dust accumulation on photovoltaic panels, Environ. Sci. Pollut. Control Ser. 27 (2) (2020) 2001–2014.
[86] A. Sayyah, M.N. Horenstein, M.K. Mazumder, Energy yield loss caused by dust deposition on photovoltaic panels, Sol. Energy 107 (2014) 576–604.
[87] W.A. Omran, M. Kazerani, M.M. Salama, A clustering-based method for quantifying the effects of large on-grid PV systems, IEEE Trans. Power Deliv. 25 (4) (2010) 2617–2625.
[88] S. Shivashankar, S. Mekhilef, H. Mokhlis, M. Karimi, Mitigating methods of power fluctuation of photovoltaic (PV) sources–A review, Renew. Sustain. Energy Rev. 59 (2016) 1170–1184.
[89] L. Grandell, M. Höök, Assessing rare metal availability challenges for solar energy technologies, Sustainability 7 (9) (2015) 11818–11837.
[90] B. Bakhiyi, S. Gravel, D. Ceballos, M.A. Flynn, J. Zayed, Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges, Environ. Int. 110 (2018) 173–192.
[91] Y. Xu, J. Li, Q. Tan, A.L. Peters, C. Yang, Global status of recycling waste solar panels: a review, Waste Manag. 75 (2018) 450–458.
[92] A.C. Nielander, M.R. Shaner, K.M. Papadantonakis, S.A. Francis, N. Lewis, A taxonomy for solar fuels generators, Energy Environ. Sci. 8 (1) (2015) 16–25.
[93] G. Ciamician, The photochemistry of the future, Science 36 (926) (1912) 385–394.
[94] M. Đokić, H.S. Soo, Artificial photosynthesis, Mater. Today 11 (12) (2008) 26–34.
[95] M.D. Kärkäs, O. Verho, E.V. Johnston, B. Åkermark, Artificial photosynthesis: molecular systems for catalytic water oxidation, Chem. Rev. 114 (24) (2014) 11863–12001.
[96] F. Lubbe, J. Rongé, T. Bosserez, J.A. Martens, Golden hydrogen, Curr. Opin. Green Sustainable Chem. 39 (2023), 100732.
[97] J.A. Sullivan, R. Abolivier, Chapter 7 artificial photosynthesis over heterogeneous photocatalysts, in: C. Pillai Suresh, Kumaravel Vignesh (Eds.), Photocatalysis, De Gruyter), Berlin, Boston, 2021, pp. 191–256.
[98] Z. Jiang, P. Wang, G. Liang, X. Wen, G. Huang, H. Song, B. Jiang, S. Jin, F. Xu, X. Ding, T.K. Kim, H. Chen, J. Yu, J. Ye, S. Wang, Homogeneous–heterogeneous hybrid artificial photosynthesis induced by organic semiconductors with controlled surface architectures, Adv. Funct. Mater. 33 (34) (2023), 2303335.
[99] S. Perathoner, G. Centi, Artificial leaves using sunlight to produce fuels, in: Angelo Basile, et al. (Eds.), Studies in Surface Science and Catalysis, vol. 179, Elsevier, 2020, pp. 415–430.
[100] S. Chabi, K.M. Papadantonakis, N.S. Lewis, M.S. Freund, Membranes for artificial photosynthesis, Energy Environ. Sci. 10 (6) (2017) 1320–1338.
[101] E. Edri, S. Aloni, H. Frei, Fabrication of core–shell nanotube array for artificial photosynthesis featuring an ultrathin composite separation membrane, ACS Nano 12 (1) (2018) 533–541.
[102] M.R. Shaner, H.A. Atwater, N.S. Lewis, E.W. McFarland, A comparative technoeconomic analysis of renewable hydrogen production using solar energy, Energy Environ. Sci. 9 (7) (2016) 2354–2371.
[103] C. Chang, B. Farnum, Artificial Photosynthesis for Solar Energy Storage: toward a Sustainable and Equitable Future, Cambridge University Science and Policy Exchange, Communications, 2014, pp. 10–11.
[104] T. Faunce, Global artificial photosynthesis: challenges for bioethics and the human right to enjoy the benefit of scientific progress, S. Cross UL Rev. 15 (2012) 21.
[105] W. Wang, W. Xiao, C. Bai, Can renewable energy technology innovation alleviate energy poverty? Perspective from the marketization level, Technol. Soc. 68 (2022), 101933.
[106] D.G. Nocera, Fast food" energy, Energy Environ. Sci. 3 (8) (2010) 993–995.
[107] B. Becker, Public R&D policies and private R&D investment, J. Econ. Surv. 29 (5) (2015) 917–942.
[108] B.K. Sovacool, C. Daniels, A. AbdulRafiu, Science for whom? Examining the data quality, themes, and trends in 30 years of public funding for global climate change and energy research, Energy Res. Social Sci. 89 (2022), 102645.
[109] V. Andrei, Q. Wang, T. Uekert, S. Bhattacharjee, E. Reisner, Solar panel technologies for light-to-chemical conversion, Acc. Chem. Res. 55 (23) (2022) 3376–3386.
[110] N.S. Lewis, Introduction: solar energy conversion, Chem. Rev. 115 (23) (2015) 12631–12632.
[111] M. Peplow, Solar Panels Face Recycling Challenge, ACS Publications, 2022.
[112] S.H. Ali, D. Giurco, N. Arndt, E. Nickless, G. Brown, A. Demetriades, R. Durrheim, M.A. Enriquez, J. Kinnaird, A. Littleboy, Mineral supply for sustainable development requires resource governance, Nature 543 (7645) (2017) 367–372.
[113] E. Cuppen, Diversity and constructive conflict in stakeholder dialogue: considerations for design and methods, Pol. Sci. 45 (1) (2012) 23–46.
[114] E. Cuppen, U. Pesch, S. Remmerswaal, M. Taanman, Normative diversity, conflict and transition: shale gas in The Netherlands, Technol. Forecast. Soc. Change 145 (2019) 165–175.
[116] S. Umbrello, M.J. Bernstein, P.E. Vermaas, A. Resseguier, G. Gonzalez, A. Porcari, L. Adomaitis, From speculation to reality: enhancing anticipatory ethics for emerging technologies (ATE) in practice, Technol. Soc. 74 (2023) 102325, https://doi.org/10.1016/j.techsoc.2023.102325.