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Popa, Eugen Octav; Melnyk, Anna

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Taking value conflicts seriously: Technological pluralism as an approach to hydrogen governance

Eugen Octav Popa *, Anna Melnyk

Ethics/Philosophy of Technology, Delft University of Technology, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628 BX, Delft, the Netherlands

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ABSTRACT

We propose technological pluralism as a governance framework for navigating value conflicts arising from technological change within the energy system. The transition to clean hydrogen serves as a case in point as it gives rise to multiple (and complex) value conflicts. Typically, governance frameworks and other strategic approaches are led by the assumption that value conflicts, to the extent that they arise, can and should be solved. We contest this fundamental assumption by drawing on insights from moral and political philosophy. By specifying the descriptive, normative, and prescriptive tenets of a technological pluralist governance process, we set out a framework for driving transitions while taking value conflicts seriously. With clean hydrogen production as a case in point, we illustrate (a) the analysis of socio-technical change through pluralist lenses and (b) the design of pluralist governance strategies for clean hydrogen. We conclude with the suggestion that technological pluralism might be suited not only for the governance of the hydrogen transition but also for taking value conflicts seriously in the current context of decentralization and inclusion promoted by recent EU energy policy frameworks.

1. Introduction

Hydrogen is ‘hot’ again! After past hype cycles have faded, there are clear signs today that we are on the brink of a systemic transition toward the long-awaited hydrogen economy [1,2]. Numerous organizations, including national governments and the European Union, have expressed unambiguous commitments for transitioning towards sustainable forms of hydrogen production [3–5]. However, despite a solid consensus on the potential of green hydrogen to contribute to the reduction of CO_2 emissions and to function as a storage solution for intermittent wind and solar, there is an ongoing discussion regarding the governance side. How can policy be simultaneously effective in accelerating the transition process but also vigilant in identifying socio-ethical risks, for example injustices, that can constitute potential barriers down the road? [6–8]. Recent studies have concluded, using social life-cycle analysis, that the environmental benefits of hydrogen transition may come at the cost of socio-political consequences [9,10]. In other words, global environmental values may conflict with community-related values making responsible governance of hydrogen transition difficult. In light of this and other challenges brought by different technologies for hydrogen production, studies have indicated the importance of developing standardization, certification, and labeling schemes as a crucial step in governing the hydrogen transition [10]. While undeniably vital, such measures can only partially address the challenge at stake and it is ultimately the governance actor that is called upon to address the resulting value conflicts that will not boil down to choosing between environmental values and social ones but will include, e.g., scalability, water use, availability of materials, durability, cost, justice, technology readiness, flexibility, integration, geopolitical risks, socio-economic consequences for vulnerable groups and more [11]. Furthermore, the governance actor must also approach these value conflicts in a state of multi-layered uncertainty including “normative uncertainty” [12] and economic policy uncertainty [13]. Hence, there is a need for a governance approach that would provide a standpoint from which such value conflicts can be identified, analyzed, and navigated responsibly. The term “governance” can refer broadly to the decentralized way in which various societal actors, government, industry, research, and civil society collectively seek and construct solutions to recognized problems [14].

In this context, we submit *technological pluralism* as a governance approach for taking value conflicts seriously within the hydrogen transition. Borrowing insights from the moral and political philosophy of

* Corresponding author.
E-mail address: o.e.popa@tudelft.nl (E.O. Popa).

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pluralism [15–18], technological pluralism provides a framework for both policy analysis and policymaking. In Section 2 we define technological pluralism by making explicit the descriptive, normative, and prescriptive commitments that a pluralist governance actor assumes. In Section 3, we then illustrate the application of these commitments to the problem of choosing technologies for clean hydrogen production, a topic of intense discussion nowadays in both academic and policy circles [19, 20]. In Section 4, we provide a set of policy strategies to facilitate the infusion of technological pluralism in hydrogen governance, and potentially in other areas of energy policy. In Section 5 we suggest avenues for further research, particularly on the assumption that technological pluralism could lead to applicable strategies in other areas of the energy sector.

2. What is technological pluralism?

The governance framework we want to develop draws heavily on the philosophy of pluralism. Although the term "pluralism" has been given slightly different meanings in moral philosophy [16,21], political philosophy [22], and philosophy of science [23], there is nevertheless a conceptual core we take here as a starting point. To be a pluralist about technology means to admit that there are multiple technological solutions for any given problem and that this multiplicity is not apparent or superficial, but rather it is essential for understanding and solving the problem at hand. Each technological solution is seen as having its specific profile of values served and values disserved, but since values are incommensurable, the governance actor cannot decide the resulting competition between solutions by extracting "optimal" technologies through cost-benefit analysis [24]; [25]. Value hierarchies can gradually arise, organizing and stabilizing the multiplicity of values involved, but the technological pluralist remembers that such priority schemes are temporary. Value hierarchies are like governance 'algorithms' that can simplify a complex problem in beneficial ways, but they are in a state of constant change due to the continuous transformation of the physical and cultural boundaries of the system [26,27]. Based on this conceptual core, let us describe in more detail the governance commitments of the technological pluralist: descriptive commitments pertaining to the world, normative commitments pertaining to the values at hand the good, and prescriptive commitments pertaining to future action. The following commitments constitute, therefore, the backbone of technological pluralism as a governance approach (see Table 1).

2.1. Descriptive commitments

The fundamental descriptive claim that characterizes technological pluralism is that the choice between different technological solutions (e.g., for producing clean hydrogen) can be analyzed as a choice between different and incommensurable values. Each technology is reconstructed as having a specific moral profile of values served and values disserved, a specificity that has many sources: the framing of the problem at hand, the primary materials utilized in building the technology, the features developed (and those underdeveloped), their use and potential misuse, etc. By assuming that values are incommensurable, the pluralist is skeptical of the idea that one value can always rise above others to form the benchmark for evaluation. Research on how technology impacts individual values such as justice [28]; [29], [30]) or responsibility [31] is surely insightful and applicable, but there is no common standard based on which to decide how much justice should be lost to an increase in freedom, how much freedom to an increase in security, how much security to an increase in responsibility, etc. But pluralists are not relativists. Values are incommensurable, but not anything goes. First, there is a rock-bottom of physiological, psychological, and social needs that should not be annulled by any new technologies [16]. Second, the incommensurability of values does not prevent stakeholders from behaving rationally in the evidence they accept [32], the dialogue procedures they adopt [33] and the stipulations they jointly adopt [11]. Reasonable choice is not rendered impossible by the existence and persistence of conflict between incompatible values, but pluralists insist nevertheless that even well-reasoned decisions are context-dependent and might need to be revised in light of new values or changed value hierarchies [34].

2.2. Normative commitments

While descriptive commitments capture the pluralists' view of the technology-society relationship, normative commitments capture how they evaluate this relationship. Of course, this evaluation cannot rely on individual values such as justice, freedom, privacy, and safety or else the diversity implied by the descriptive commitments is annulled [17]. However, normative commitments can function as meta-values that provide guidelines for the interaction between values (in practice, for the interaction between the different stakeholder and their preferred value sets and value hierarchies). Three such meta-values are presumably the most relevant for technology governance: fallibilism, agonism, and integrationism.

Fallibilism states that policy should take into consideration the scenario in which one's convictions about technology and its moral impact prove to be wrong. Fallibilism, originally a concept of liberal political philosophy [35], has provided the starting point of numerous approaches to science and technology governance such as 'reflexive governance' and 'responsible research and innovation' [14,31]. Being committed to fallibilism means understanding the socio-technical system as a dynamic system that changes in ways that invalidate previously accepted beliefs. This goes against the linear model of innovation, in which knowledge uncertainty diminishes gradually as new scientific discoveries increase our positive knowledge about reality; whatever the value of this model might be for understanding scientific knowledge, it does not apply to normative matters, and thus, scholars speak of *normative uncertainties* as a constant feature of technology governance [12]. Pluralists are not pessimists, and they are surely not technophobes, but they remember the saying that there is no such thing as a free lunch and are generally wary of technological hypes. This is confirmed by numerous cases in the history of technology where tremendous suffering was brought about by 'miracle' solutions such as DDT (Dichlorodiphenyltrichloroethane), TEL (Tetraethyl lead), CFCs (Chlorofluorocarbons) and asbestos.

Table 1
An overview of techno-pluralism as a governance framework.

	Main question	Categories	Maxims
Descriptive commitments	How do technologies relate to values?	Plurality	There are many technological solutions
		Incommensurability	They have incommensurable value profiles
		Value conflict	They create value conflicts
Normative commitments	What does it mean to "do good" with technology?	Fallibilism	We can always be wrong about regarding facts and values
		Agonism	Competition benefits the system
		Interactionism	Values interact Acts have systemic impact
Prescriptive commitments	How can you "do good" with technology?	Complexity	Analyze values and arguments
		Humility	Piecemeal social engineering
		Equality	Dominance is unavoidable, but avoid value tyrannies

Agonism is the view that conflict is instrumental to responsible democratic governance [36–38]. In the case of technology governance, agonism entails that some institutionalized competition among alternative technologies is preferable to deep technological lock-in of one 'winner,' even in the (exceptional) case in which the winner appears to optimally satisfy all stakeholders' requirements [39]. Competition is essential for maintaining an overall long-term balance between values served and disserved. Scholars working on the governance of science and technology typically assume a conciliatory view of stakeholder interaction according to which stakeholder groups can and should collaborate ('across helixes') towards mutually favorable outcomes [40]. To the pluralist, this ideal will seem both descriptively and normatively inaccurate, since striving towards consensus brings through the back door the belief in a resolution to everyone's satisfaction, a final satisfaction of all relevant values. Instead, the pluralist will think it is better to 'stay with the trouble,' even after one solution has momentarily won by appearing to be the most tolerable compromise.

Integrationism advises against oversimplifying the value dynamics around the technology under discussion. Rooted in climate justice literature [41], integrationism urges the analyst to reconstruct the values impacted by a technology as well as how these values interact, relate and change at different levels within the system [34]. The type of integrationism relevant for our proposal builds on the assumption that inquiry into values and their dynamics provide access to moral knowledge of what is at stake in each context of agonism. Choices between technologies embodying different values do not occur in a void and different moral profiles of technological solutions result in value conflicts that can contribute to larger issues such as power imbalances, exploitation of labor and resource, and environmental degradation. Of course, complexity can be episodically forgotten. The effects of a technological choice can always be simplified into a useable model with a limited number of values on which we deploy clear-cut decision criteria. However, integrationism urges us to always remember the relations that were 'modeled away' to capture the effect of a decision within its wider social, technological, and ecological context. The sole focus on the problem-solving capacity of technology becomes normatively unacceptable.

2.3. Prescriptive commitments

To the descriptive and normative commitments above we add a series of *prescriptive commitments* that formulate strategies for action. Pluralism is not only a standpoint from which to describe and evaluate the world but also to change it. The question before us is, therefore, "How should a technological pluralist respond to a given process of socio-technical change?" This is arguably the most difficult feature of pluralism since both the descriptive commitment to the incommensurability of values and the normative commitment to fallibilism seem to undercut any action that would favor one value or another (and any action does favor one value or another!). We can understand why Crowder refers to this as "the problem of value pluralism" [42]. In practice, paralysis is avoided by accompanying policy responses with adjustment mechanisms for the situation in which actors are proven wrong or values previously disfavored need to be served. Consequently, the prescriptive response to the problem of value pluralism from scholars in different disciplines has been extremely diverse and usually tailor-made for the problem at hand. Three such approaches will serve as examples: staying with complexity, exercising humility, and maintaining equality.

First, the pluralist actor is characterized by seeking complexity in a systemic view of socio-technical change. As a matter of course, therefore, the pluralist is averse to simplifications. "Keep it complex!" as Stirling [43] suggests. Decision-making moments are not seen as the optimization of technology on some selected values but rather as balancing acts between the multiple conflicting values at hand [11]. The pluralist actor is not seeking the most efficient or the most sustainable or, generalizing, the most *x*-able technology, but rather keeps in focus the many "trade-offs" involved in every decision and seeks to maintain a "precarious equilibrium" between the different ways in which reality could prove her wrong [44]. The pluralist governance actor is an argumentative being in that for her policy analysis is "argumentative policy analysis" consisting in a dialectical reconstruction of alternative pathways *as* alternative argumentation structures exhibiting complex structures [45]. The reconstruction of arguments not only dispels the illusion that there is but one 'good' solution to the problem at hand, but clarifies the values at stake and the.

Second, the pluralist favors incremental socio-technical change as opposed to utopian disruption. Governance instruments, especially those directed at public participation, are seen as "technologies of humility" [46]. Pluralist governance is, therefore, a form of "piecemeal social engineering" [47] that seeks to prepare for the risk of unexpected change, particularly at a systemic level where flexibility and adaptability can be instilled across a variety of technological choices [26]. The governance of socio-technical change can temporarily favor drastic intervention against impending catastrophe, but it remembers the values left behind and the "late lessons from early warnings" even in its most disruptive episodes [48].

Third, the pluralist follows the strategy of 'complex equality' among values [18,25]. First developed by Michael Walzer and later applied across various disciplines, the concept of *complex equality* is best understood in contrast to the simpler notion of *simple equality*. Striving for simple equality among values means ensuring no one value is served more than another. Simple equality is impractical, as keeping all gains and losses equal across multiple decision points is not only unachievable but also ignores contextual determinations. In contrast, the pluralist search for complex equality aims to prevent any single value from systematically dominating across different decision areas and making other values commensurable in their relationship with this dominating value. Serving values unevenly is acceptable, both short term and long term, so long as dominant values do not "buy off" other values, undermining their social meaning. Walzer labels this systematic dominance as *tyranny*, borrowing Blaise Pascal's view of tyranny as seeking by one means what can only rightly be obtained by another. In summary, complex equality describes a state where smaller inequalities balance each other out without any one value overtaking the broader system.

We do not wish to suggest that other approaches reject these tenets altogether – but we do suspect that they take value conflicts somewhat less seriously in various ways. Consider for example the Multi-Criteria Decision Analysis (MCDA) approach, a widely used method for the comparative evaluation of complex decisions with multiple competing criteria [49]. Now, some approaches are quick to point out that "objectives" are incommensurable, yet the method itself boils down to a decision-making process that gradually assumes the existence of a rational, cvasi-algorithmic methodology for responding to this incommensurability [50]. The assumption of comparability has slipped through the back door and forces fundamentally different values—such as environmental sustainability and economic growth—onto a common scale. This leads to reductionism, where deep ethical or cultural disagreements are artificially converted into numerical weights, masking the true nature of conflicts. MCDA also promotes the illusion of objectivity, as it requires decision-makers to assign trade-offs between values, even when the real issue is whether certain values should be compromised at all. By reducing complex moral and political conflicts to mathematical calculations, MCDA often obscures rather than resolves value disagreements, making it an inadequate tool for decisions where ethical and social trade-offs are at the core. Instead of fostering meaningful dialogue, it risks oversimplifying conflicts, leading to decisions that appear rational but fail to acknowledge or understand deeper normative tensions in terms of the values involved.

In the next step, we illustrate the application of the governance approach introduced in the previous sections on two aspects of hydrogen governance: pluralist policy analysis (Section 3) and pluralist policy design (Section 4). Given space limitations, these two will only be developed at the level of detail necessary to illustrate their specific focus on value conflicts.

3. Technological pluralist approach to hydrogen governance

Water electrolysis, the splitting water electrochemically into hydrogen and oxygen, is currently seen as the main alternative to fossil-based production of hydrogen ([51,52]; [53]; [54]). Many national and international organizations have shown sustained support for water electrolysis. The national hydrogen plans and strategies published since 2017 rely, either fully or in part, on water electrolysis to do the job.[1] It is especially easy in this context for electrolytic hydrogen to be subsidized since both the funding and the envisaged certification schemes favor water electrolysis as the pathway towards "green" hydrogen [55]. In 2024, the newly established European Hydrogen Bank allocated €720 million to produce 1.58 million tons of renewable electrolytic hydrogen over ten years.[2] Similarly, the H2Global Foundation, a German-based government initiative, announced the results of a €900m auction for the production of ammonia derived from electrolytic hydrogen.[3] The Dutch government also announced an approximately €1bn subsidy (€998,330,000) for "hydrogen production via electrolysis"[4] a decision that was in line with the earlier announced strategy of "concentrating on electrolysis".[5] Finally, the Solar Energy Corporation of India awarded support for nearly 2.8 GW of electrolyzer capacity in 2024.[6] The support for electrolysis can also come indirectly through a sustained critique of other decarbonizing solutions. For example, 'blue hydrogen' produced through steam methane reforming (SMR) with carbon capture (CCS), is seen as an undesirable continuation of the entrenchment of fossil fuels in the energy system even though it has clear advantages in certain scenarios [56–58]. These are just isolated examples, but they are sufficient to paint the picture of a clear winner in a value conflict dominated by two values: sustainability understood as CO_2 emissions and cost [59]. Electrolysis is more expensive than traditional fossil-based methods, but we accept this reduction in affordability due to the technology's serving of environmental values. The choice is thus one of environment over cost as portrayed in Fig. 1 below.

This simplified trade-off is a good starting point, and it has been the starting point of various life-cycle analyses of hydrogen production technologies [60]. In a pluralist perspective one would further seek complexity in two different but complementary directions: through increased depth of analysis or breadth of analysis. We will develop both for illustrative purposes, starting with the increase in depth of argumentative analysis which consist in understanding the subordinate argumentation and considerations that feed into the main trade-off. Let us start with the high emissions of fossil-based hydrogen. On the one hand, fossil-based methods of producing hydrogen are high in CO_2 emissions, but, if these emissions could in principle be curtailed by CCS, the already-existing infrastructure and technology for hydrogen production could be more rapidly utilized leading to a faster system diffusion of hydrogen as a replacement fuel [61,62], especially in Gulf states [63]. The technology of CCS, while it has had some success in pilot projects, is nevertheless highly uncertain and has been contested by advocates of decarbonization both on technical grounds and on socio-economic ones [64]; [65]. In other words, the presumed *low cost* of fossil-based hydrogen production typically excludes the social and environmental cost of carbon emissions [66] as well as other climate impacts associated with the use of natural gas [67]. The oil and gas industry has simply been around for longer compared to the electro-chemical industry and has benefited from constant governmental support. The difference in cost, then, might not reflect the actual socio-economic burden of the fully-fledged technologies, but their different stage of development.

Turning now to the right side, it is beyond doubt that the process of water electrolysis is environmentally cleaner compared to SMR and other fossil-based methods. However, broader life-cycle analyses have shown that, green as they may be, the environmental impact of electrolysis is far from negligible ([68]; [54]). Green electrolyzers compete with green electricity on a wider picture of decarbonization [69] and the actual CO_2 reduction effects of electrolytic hydrogen need to be calculated taking the wider policy and technological context into consideration [70–72]. The 'greenest' electrolyzers directly connected to renewables present various technical and economic difficulties given that renewables are intermittent while electrolyzers require constant operation under a minimum load [73]. Then there are questions regarding technology components and performance. Quite aside from emissions, some electrolysis designs require rare materials such as iridium and specialty materials such as the Nafion® membrane the production of which is the source of CO_2 emissions and geo-political constraints [74]; [58]. But if electrolyzers are connected to electrical grids in regions with high carbon intensity, their environmental benefits decrease significantly [72]. The best way to approach all these issues from a policy perspective, what criteria and certification mechanisms are needed, is still a matter of intense debate that we do not need to further analyze here ([75]; [76]). The point is rather that the degree to which green hydrogen serves environmental value is much more complex (and uncertain) than the full policy support of electrolysis would suggest. Finally, similar complexities need to be taken into consideration when using the 'high cost' counterargument against electrolysis. When considering environmental cost, improved engineering, scaled-up production, and governmental support (including carbon taxing of fossil-based technologies), green hydrogen might not be that expensive after all. However, this cost, as well as its evolution during life-cycle disruptions, remains notoriously difficult to establish, so current estimations usually contain a significant degree of uncertainty ([77,78]; [54]).

In Fig. 2 below, we illustrate the increase in the complexity of the initial value analysis by the addition of these considerations (the gray squares) which function as qualifiers or subordinate argumentation to the initial pros and cons. Technological choice, even when seen restrictively from the perspective of one trade-off between environmental and economic value, can prove to be quite complex. The relationship between any given technology and any given value is hardly ever a straightforward process of creating or destroying value. For example, we see that electrolytic hydrogen both serves environmental values (through the reduction of CO_2 emissions) and disserves the same values (due to specialty materials and other CO_2-intensive components). Similarly, we see that fossil hydrogen is cheaper than electrolytic hydrogen, serving economic values short-term, but that we must consider how the depletion of fossil reserves and accelerated climate policy can turn short-term affordability into long-term payments.

A second form of complexity concerns *breadth* of argumentative analysis. The trade-off shown in Fig. 3 still revolves around only two value sets. Integrationism as discussed above pushes the analyst to identify other impacted values, especially if they are affected negatively by the technologies under discussion. For illustrative purposes, we discuss here briefly the impact of hydrogen on two other values: *justice* [56]; [6] and *freedom* [58].

Justice. There are various interactions between the hydrogen transition and the value of justice, interactions that can be seen as falling within the scope of recent literature on the concept of energy justice

[1] An updated list of countries and the respective documents can be found here: https://research.csiro.au/hyresource/policy/international/.

[2] https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/competitive-bidding_en.

[3] https://www.hydrogeninsight.com/production/breaking-h2global-announces-first-results-of-900m-auction-for-green-hydrogen-imports/2-1-1676337.

[4] https://english.rvo.nl/subsidies-financing/owe.

[5] https://zoek.officielebekendmakingen.nl/kst-32813-1314.pdf.

[6] https://www.seci.co.in/Upload/New/638603791123234059.pdf

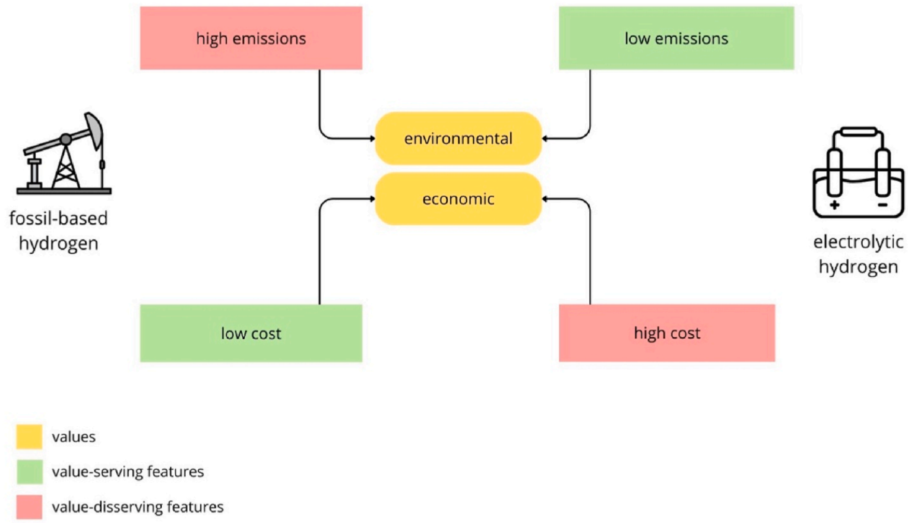

Fig. 1. Main trade-off between sustainability and cost in water electrolysis.

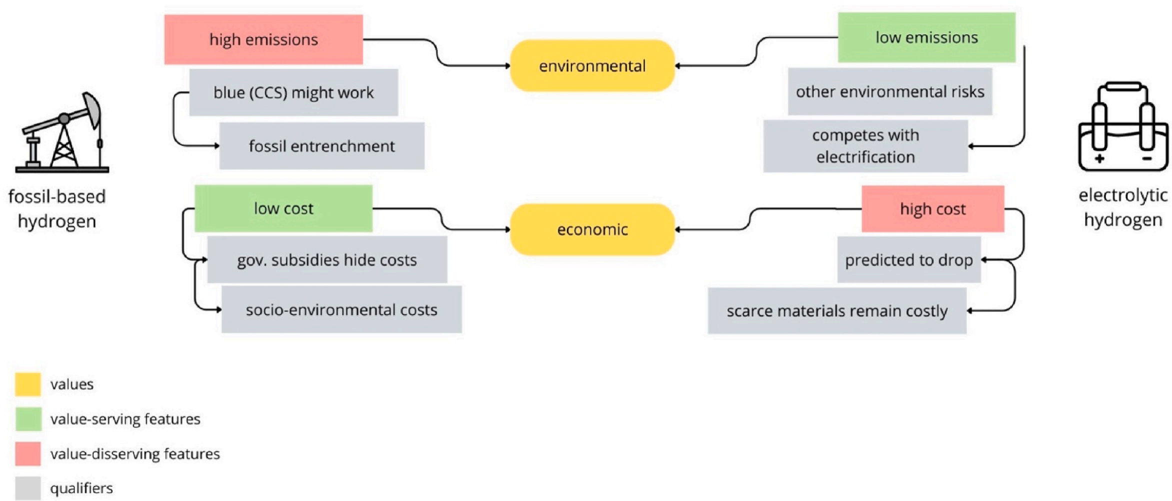

Fig. 2. Main trade-off between sustainability and cost in water electrolysis (depth).

[79]; [29]. For example, increased taxpayer burden and energy poverty can occur either through continued environmental damage from fossil-based methods (left side) or as a result of major investments in new hydrogen infrastructure. The risks of both climate change and climate action can be distributed unevenly, rippling through from, e.g., higher-priced hydrogen to higher-priced steel to higher-priced goods etc. The cost of clean hydrogen is predicted to decrease as a result of economies of scale, but it is difficult to estimate when this will take place. In the meanwhile, recent analyses put the levelized cost of hydrogen at €12–14/kg_{H2}.[7] Aside from matters of distributive justice regarding costs, the technology of green hydrogen will initially tend to favor investments in countries with already-existing knowledge and infrastructure (particularly high-performing electricity grids) and can lead, for example, to an increase in systemic inequality between North-Western and South-Eastern countries within the European Union. And building on the idea that green hydrogen is primarily envisaged as a centralized, 'big-industry' solution, stakeholders have urged governments to also apply more local and demand-side solutions that can be more efficient although more difficult to model and trace quantitatively [56]; [80].

Freedom. The development of a global hydrogen economy can have a significant impact on individual freedom for it can, on the one hand, decentralize the energy system to create more local energy communities [81]; [82]. At the same time, if maritime transportation of hydrogen amplifies, the development of clean hydrogen can lead to new geopolitical dependencies between countries as part of a global supply chain [58]. If green hydrogen becomes an important energy carrier for a certain state or region, they will be much more dependent on other hydrogen-producing states or regions and might be faced with difficult moral choices between freedom and energy security ([83]). Reversely, countries that have access to cheap green electricity (due to geographical advantages), can produce electrolyzers easily, or can harvest and transport requisite noble and rare metals might experience an increase in geo-political liberty and a more decentralized energy system that is not dependent on import. Scholars have also noted the possibility of creating new forms of colonialism and land grab [56] along with new forms of environmental damage such as the exponential increase of water usage [84] or new forms of toxicity resulting from the degradation and disposal of novel materials [85].

[7] https://www.rijksoverheid.nl/documenten/rapporten/2024/05/30/bijlage-1-tno-2024-r10766-evaluation-of-the-levelised-cost-of-hydrogen-based-on-proposed-electrolyser-projects-in-the-netherlands-definitief.

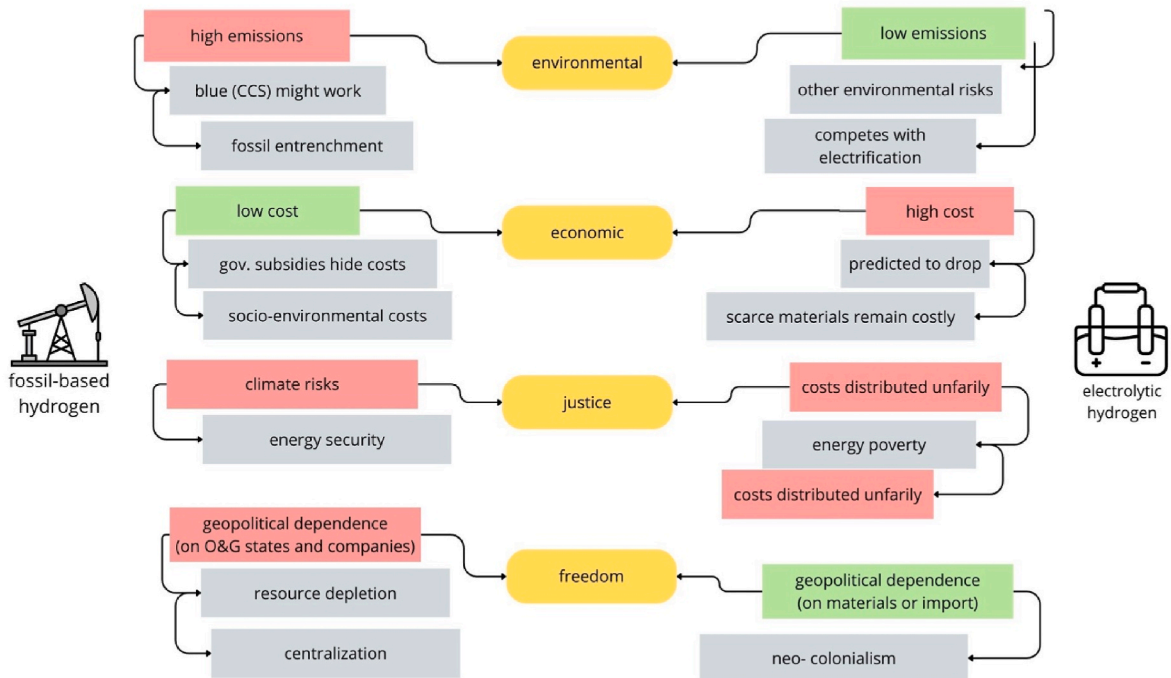

Fig. 3. Value trade-offs of electrolysis.

Finally, the breadth of analysis can also be increased by taking into consideration other technological options for producing (clean) hydrogen Fig. 4. Here we have focused on electrolysis as a case in point but of course this is not the only option around. Comparative studies have shown that each of these options comes with a complex technical profile, differing from others on parameters such as efficiency, sustainability, water usage, energy usage, availability of required materials, commercial readiness, profitability, safety (including toxicity), lifespan, societal impact, capex, and land use [86–88]. This vastly increases the breadth of analysis in a way that cannot be fully illustrated here. Technologies that are nowadays unusable on a commercial scale such as (5) photolysis and (6) radiolysis, might encounter future breakthroughs that can completely disrupt the scheme of evaluation criteria in unpredictable ways, for example, if we can harvest and employ solar energy in much the same way plants do, through what is sometimes called "artificial photosynthesis" ([89];[]). Under the assumption that absorption can be maximized, then parameters such as efficiency that are currently prioritized when ranking technological solutions might decrease in importance. We nowadays imagine the use of solar energy in terms of its conversion to electricity through panels; but if the artificial photosynthesis project succeeds, then the photochemical conversion of CO_2 to useable fuels can revolutionize the way we think about energy conversion, thereby decreasing the relative importance of efficiency. Although since there is no such thing as free lunch, we should specify that in that case land use becomes increasingly important, which is already a point of worry in the development of renewable technologies for fuel production ([84]; [53]). Similar considerations could be advanced for possible breakthroughs in other areas such as nuclear energy [90] or floating wind-to-hydrogen ([91]). It is not at all certain that such breakthroughs on other technologies will score high on the given values, but it is significant that electrolysis appears today as a relatively underdeveloped technology precisely due to long-term overreliance on the tried-and-true method of SMR. The fallibilism introduced above suggests humility in this case: there is little basis to assume that we can dispose of these alternative means of hydrogen production, namely, that electrolysis will prove singularly sufficient to answer the "terawatt challenge" for the topic of hydrogen.

4. Policy measures from a pluralist perspective: observing the space left behind

Policy analysis is only the first step in a full-fledged governance process. The previous section contained an illustration of a pluralist approach to policy analysis that focuses on value conflicts between diverse technological solutions. With this as a starting point, we will now discuss several policy measures that follow from this analysis. For reasons of space, we will limit ourselves to a brief discussion of each measure indicating how it relates to pluralist commitments and how it can be implemented.

4.1. *Technological diversity as design for value change*

The diversity of technological options has been a central theme in technology policy over the past decades, due partly to a growing understanding that technological harm can be minimized through the availability of alternatives [92]. However, although few will be against risk mitigation through diversification, it is notoriously complicated to institutionalize diversity. Market-driven innovation locks in easily. Once stakeholders see a technology as having 'won' the battle with alternatives as in the case of electrolysis, the support for 'losing' technologies becomes increasingly difficult [25]. Still, the history of technology is replete with episodes in which the exclusive focus on a certain technology, together with the systematic disregard for alternatives, increases the cost of replacement once the dominating technology was rejected for societal or environmental reasons [48]. As mentioned, electrolysis is itself precisely such a well-known technology that survived underdeveloped in the shadow of SMR as the dominating winner [93].

The institutionalization of diversity does not need fundamental changes relative to current technology policy. For example, it makes sense from a pluralist perspective to earmark unused funds from higher-TRL subsidies – e.g., from the Hydrogen Bank and H2Global – for financing fundamental research or lower-TRL research into hydrogen technologies. In this way, even though (alkaline) electrolysis remains the major winner of these auctions, the technological lock-in is balanced by a constant underflowing support of alternative innovation paths. To be sure, policymakers would not challenge the status of electrolysis as

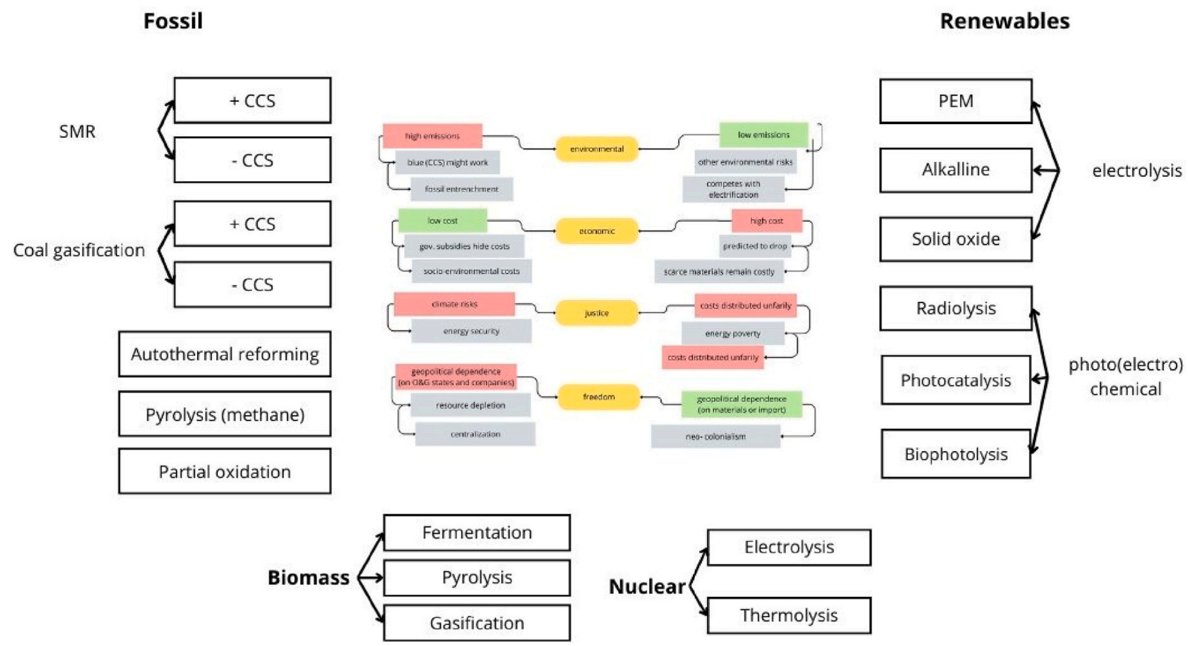

Fig. 4. Multiple values, multiple alternatives, complex conflict.

the rightful winner currently, but they would rather acknowledge (humbly) that technology is not without its disserved values and potential drawbacks. If we discover later that centralized, locked-in electrolysis needs to be partially or fully replaced, covering the space left behind through alternative technologies will minimize the time and cost of this replacement. The concomitant financial support of alternative technologies is, therefore, a prophylactic move that can improve the adaptability of hydrogen markets to techno-moral change – a form of "designing for value change" [26]. However, it should not be seen as simply a form of risk mitigation, a move whose reasonableness derives only from pessimistic scenarios in which the solution of electrolysis is annulled by techno-moral change. Rather, the continued support of alternative technologies that are in their infancy can be the source of new insights and, in the long term, the source of a more diversified energy system where specific technologies (e.g., pyrolysis, photocatalysis) are deployed on precisely those niches where electrolysis fares the worst. In short, what is gained from 'staying with the trouble' on a scientific level is not knowledge for the sake of knowledge but rather a source of insights into the fundamental energy processes needed for the future.

4.2. Local interventions: "cycling," firewalls, and casuistry

The governance strategies discussed by Thacher and Rein ([94]) constitute responses to value conflicts because they assume that "instrumental rationality […] can only determine how policymakers can achieve each of their goals in isolation, not how to resolve the conflicts among them" ([94], p. 457). In response to fundamentally irreducible value conflicts, the authors discuss the strategies of: *cycling* (considering the decision repeated over time and cycle back and forth between serving the two incompatible values, achieving an equilibrium over time), *firewalls* (ascribe the responsibility to defend different values to different institutions each with a simplified version of the problem) and *casuistry* (design projects and institutions such that case-by-case reasoning is allowed until gradually stakeholders can work with a bottom-up 'taxonomy of moral cases' which can be used as exemplars). Other policy examples are the ones discussed by Paxton from an agonistic perspective such as the institutionalization of "contestation days" where citizens are called upon to understand and deliberate about the major technological changes that occur in their lives [95]. The dialogical aspects of these will be discussed below. What we wish to highlight here is that governance processes can be devised without committing to a certain value as being the most relevant across situations. A pluralist governance approach keeps the value conflict open for unexpected priorities of values whereas it would be very difficult, for example, to deprioritize safety under the precautionary principle, to deprioritize justice within the field of energy justice [79] or responsibility under responsible research and innovation [31]. Such approaches can only theoretically develop towards instruments for reconstructing depth, not breadth, of value conflicts. Indeed, this is how such approaches eventually developed. For example, the concept of energy justice is broken down into different types of energy justice: distributional justice focuses on the equitable allocation of energy resources and burdens, procedural justice emphasizes fairness in decision-making processes related to energy, recognition justice acknowledges historical and ongoing injustices faced by marginalized groups, restorative justice seeks to correct past and present energy injustices through reparative actions [96]. Valuable though these distinctions may be, they illustrate the limitation of a one-value approach to governance, starting with the analysis of policy options through the lenses of the one selected value [6].

4.3. The institutionalization of agonism as means for path creation

The institutionalization of dialogue can be seen as a remedy for what Walzer calls "tyranny," the situation where a specific decision or artefact comes to dominate society to such an extent that doubting it becomes taboo [18]. Through institutionalization of dialogue, governance actors engage in path creation and neutralize "discussion stoppers," i.e., discourse through which stakeholders seek to stifle societal dialogue [97]. The institutionalization of dialogue can lead to "discussion starters" such as revisiting weak spots (bringing back forgotten or downplayed disadvantages of a technology), resizing the problem (approaching the problem from a different scale such that the existing solution appears to be less acceptable), redefining the game (stipulating into place new criteria and values to be used in evaluation) and renegotiating semantics (redefining terms used to describe the technology or its function). In our case, the simple value trade-off between sustainability and cost is currently reinforced by public discourse surrounding the label of "green hydrogen." Various organizations within the energy sector describe hydrogen in these terms, e.g., "Green hydrogen is a clean energy source that only emits water vapor and leaves no residue in the air, unlike coal and oil" . The same applies to academic literature. Variants of the summary below can easily be found in many papers discussing the decarbonization of hydrogen ([98]). For the most part, agonism is avoided because institutionalized interaction is not directed towards exhibiting conflict but towards solving it. For example, in the academic domain, national policies encourage scholars to focus on a certain niche production method, to build an academic profile and report on their technology-specific discoveries. Each production technology is a separate field of research and individual and even group expertise covering smaller themes such as catalyst development, process optimization and integration, techno-economic analyses, environmental impact, and many more. For example, researchers working on SMR can justify their choice by pointing out that electrolyzers have not yet been sufficiently developed, while scholars working on electrolysis can point out that, compared to SMR, electrolysis "is an effective and clean method to produce high-purity hydrogen by using renewable energy" [73]. Much more agonistic are non-academic contributions such as the 2020 brief "The Hydrogen Hype" by the Corporate Europe Observatory[8] and various critical editorials on both the technology side[9] and the policy side[10].

Agonism can be institutionalized, first, through low-threshold stakeholder dialogues that are focused on technology choice and the value trade-offs involved, rather than the development of specific choices [87]. Similarly, the institutionalization of agonism can take place through subjecting technology choice to public participation and citizen dialogues. For the sake of comparison, consider two public meetings held in 2023 in the UK on the subject of hydrogen use for urban heating. Both meetings, one in Ellesmere Port[11] and the other in Redcar,[12] included both experts (researchers, engineers, industry representatives etc.) and non-experts and resulted in heated debates on the many values implicated in the trade-off, values such as safety, cost, technological lock-in, fairness, and many more. These consultations offer an example of a setting for institutionalized agonism. Although not focused on the production of hydrogen but its use, the "competition" between alternatives was a central topic since hydrogen was offered as a solution instead of the more costly heat pumps.

4.4. Taking value conflicts lightly

The transition toward clean hydrogen in the Netherlands has been slowed by the failure to take value conflicts seriously, particularly regarding environmental concerns and regulatory hurdles [99]. While hydrogen production via electrolysis from renewable energy remains the long-term goal, hydrogen derived from natural gas and residual gases with carbon capture and storage (CCS) offers a more immediate solution to reducing emissions. This approach plays a significant role in the Dutch national carbon reduction strategy. One key initiative in this effort is the H-vision project in Rotterdam, which aims to produce low-carbon hydrogen by capturing and either storing CO2 in empty gas fields under the North Sea or using it as feedstock for basic chemicals. This project is part of a broader effort to integrate CCS into the national hydrogen strategy. A critical component of this strategy is the Porthos project, a joint venture involving Gasunie, the Port of Rotterdam, and EBN. Porthos is designed to facilitate CO2 transportation and storage, making it a flagship CCS initiative in the Netherlands. However, progress on the project was significantly delayed due to a lawsuit filed by Mobilisation for the Environment (MOB) over concerns about nitrogen emissions during construction. The Netherlands has been grappling with a nitrogen crisis, as excessive nitrogen emissions from agriculture, industry, and transportation threaten biodiversity. Despite significant reductions over the years, regulatory scrutiny remains stringent. In November 2022, an interim court ruling determined that the nitrogen construction exemption for Porthos did not comply with European Nature Conservation Law, necessitating an individual nitrogen impact assessment for the project ([99]). To mitigate further delays, the Dutch government took the unprecedented step of assuming temporary liability for financial risks related to Porthos, recognizing its potential to reduce CO2 emissions by 2.5 million tons annually critical for achieving climate goals. Delays in permitting processes stemming from nitrogen-related legal challenges have had broader implications, slowing the construction of essential infrastructure, including housing and renewable energy projects. In August 2023, the Council of State ruled that Porthos could proceed after determining that nitrogen emissions during construction posed no significant environmental threat. This paved the way for a final investment decision in October 2023, with construction set to begin in 2024. Despite these advancements, the controversy surrounding Porthos illustrates how unresolved value conflicts—balancing decarbonization efforts with environmental protection—continue to impede the energy transition. Addressing these conflicts proactively will be essential for accelerating the deployment of clean hydrogen and CCS technologies in the Netherlands and beyond.

5. Conclusion: towards technological pluralism in EU energy policy

We have proposed *technological pluralism* as a governance approach to hydrogen. Our main message is that we need a governance framework from which to analyze and devise policy in such a way as to capture the complexity and uncertainty of a systemic technological transition. To clarify our starting point, we have made explicit the basic tenets of this approach (Section 2). These are the core descriptive, normative, and prescriptive commitments of pluralist governance. The translation of these commitments into practice was illustrated in matters of policy analysis (Section 3) and through various examples of dealing with irresolvable value conflicts (Section 4). These measures "take values conflict seriously" in the sense that they do not assume that values converge towards one technology that needs to be identified and optimized, nor do they assume that there is one definition and resolution of each conflict. This is also our main contribution to the literature on energy governance. Currently, the great majority of governance frameworks either ignore value conflicts by focusing on one specific value – for example, the value of justice in the energy justice approach [96] – or they direct their stakeholders towards cooperative, conciliatory interventions that create the illusion that unbridgeable differences will not arise [100]; [14]. Meanwhile, comparative evaluation studies (through life-cycle analysis) focus on technology-related quantifiable values in order to compare the performance of alternative technologies [86]; [60]. Pluralist governance takes value conflicts seriously in that it attempts to integrate obvious and hidden value conflicts, and, perhaps even more importantly, it rejects the assumptions that these conflicts have an optimal solution – a 'best performance' solution. The NGO representative and the industry stakeholder and the policy maker, despite all their common ground and their joint acceptance of grand challenges, are defined by fundamentally different hierarchies of values, whether they believe in those hierarchies or follow them as part of their institutional activity [39]. Of course, some conflicts might be easy to solve, and we do not mean to suggest that 'deep disagreements' are bound to occur and stifle any attempt at cross-sectoral cooperation. But the risk of taking value conflicts *too* seriously in this way is, for this moment at least, the relatively smaller one.

By way of conclusion, we can now place technological pluralism as a

[8] https://corporateeurope.org/en/hydrogen-hype.

[9] https://blog.ucsusa.org/julie-mcnamara/the-big-hydrogen-cash-grab/.

[10] https://about.bnef.com/blog/us-hydrogen-guidance-be-strict-or-be-damned/.

[11] https://www.bbc.com/news/uk-england-merseyside-66165484.

[12] https://www.theguardian.com/environment/2023/dec/14/hydrogen-village-plan-in-redcar-abandoned-after-local-oppositiion.

governance approach in the wider EU context of energy policy. Over the past two decades, EU energy policy has increasingly encouraged the involvement of citizens in the energy system and the creation of energy districts/communities. However, as the empowerment of citizens becomes further realized and further institutionalized (especially in the policy context set by the *European Green Deal*), the predominantly procedural struggles of the past concerned with 'opening up' the policy process will gradually be replaced by the predominantly *moral* struggle of understanding and dealing with the resulting value conflicts. In other words, "it is becoming clear that these technical changes cannot be achieved without concomitant societal changes" [101]. The present proposal can be seen as a governance framework that can make sense of, and remains adaptable to, these societal changes. Of course, the procedural struggles are not thereby resolved. We have here worked only with small vignettes of what it means to approach technology governance pluralistically and we must continually think about how to 'open up' the process at various points and how to become sensitive to values left behind. As technology is democratized, we increasingly stumble upon the problem of pluralism – namely, that when values conflict there is no easy way out, that every decision is 'harmful' to some degree from the perspective of the values disserved by that decision [42]. It is good that we discover new value conflicts in our technologies, but if the newly discovered value conflicts are predominantly solved in the interest of some values at the expense of others, the complicated exercise of 'opening up' loses its initial force. What is the point of 'opening up' to different values if we 'close down' in favor of one value or a happy few? Values will have to yield to each other through different hierarchies. Fairness is important, but so is health, liberty, equality, safety, well-being, food, tradition, family, security, and many more. Current analyses of the hydrogen economy fail to capture this complexity and analyze the status quo in terms of cost, environmental impact and geopolitical risk derived from critical materials [102]. This is surely a good first step, but the approach proposed here urges us to allow value conflicts to weave themselves into both policy analysis and policymaking.

Finally, a word on the limitations of the present proposal. The development of a governance framework for a systemic technological transition is a critical step in shaping future policies and interventions. However, at an early stage, such a framework—being largely conceptual—faces significant limitations that may hinder its applicability, effectiveness, and adaptability. One key limitation is the lack of specificity. At the initial stage, the framework primarily consists of guiding principles rather than concrete mechanisms for implementation. While formulating these principles is necessary for a critical reflection on current governance paradigms, the lack of operational details makes it difficult to translate these ideas directly into the practice of regulatory structures, enforcement mechanisms, and new stakeholder behavior. However, the current framework is devised precisely to absorb such unknown unknowns regarding the hydrogen transition which is known to "involve significant trade-offs" between different values [3]. While 'the hydrogen economy' is moving relatively slowly from a systems perspective, emerging technologies evolve rapidly, often in unpredictable ways, and the mechanisms for continuous revision and reflexivity proposed here can ensure robustness and applicability in real-world governance contexts.

Credit author statement

All authors contributet to: Conceptualization, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editingIn addition, Eugen Octav Popa also contibuted to Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

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

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