

A catalytic regulatory framework for accelerating the nascent sustainable innovation field

Abstract

In the face of grand challenges threatening existing socio-technical systems, scholars and policy makers have recognised the significant role of regulatory agencies in accelerating sustainable innovations (SIs) that address societal challenges. Yet, advocating for regulatory activities to directly influence the commercial transition of SI fields has remained an unsettled debate; a conundrum that is weaved with intricately reasoned concerns about challenges in defining regulatory framework for a nascent field, and the tendency of regulators to pick winners (or losers) for the market economy. In this paper we argue that this concern may be addressed through framing anew the mechanism for regulatory interventions and conceiving the role of regulators as contributing a web stakeholder activities and relationships geared towards fostering SIs. Specifically, we draw on the functional principles of a catalyst in a chemical reaction to establish a robust bases for regulatory actions to have a direct effect on the commercial transition of SIs and present a conceptual framework of *catalytic regulation* and *sustainable innovation* to unveil core insights from which both academic discourse and policy making on regulation and innovation can benefit.

Introduction

Several calls to transition existing socio-technical systems towards sustainable ends has rendered the development and commercialisation of innovations that address grand socio-ecological and economic challenges a dominant scholarly arrestations on new product innovation in recent times (Schiederig et al., 2012). Yet, the emerging sustainable innovation (SI) field at the outset of its commercial life remain plagued with fluxing technological concept, ill-defined dominant designs, and inchoate sometimes market structures (Juntunen et al., 2019; Reficco et al., 2018). This has led to further challenges imposed on—and posed by—regulatory agencies whose legitimate mandate as gatekeepers of public safety is to ensure that new product innovations conform to approved quality and safety standards (Boakye et al., 2022; Wiegmann and Roca, 2021). Thus, as the activities of this non-market stakeholder continue to take salience in the innovation process, we conceive that the competitiveness and survival of the sustainability-oriented innovating firms is implicated in the support of these regulatory institutions

(Driessen and Hillebrand, 2013; Dewick and Miozzo, 2002). This implies that spurring a widespread application and commercial success of SIs is, in greater part at least, contingent on regulatory policies and practices that promote innovative responses to the pressing needs of socio-technical change by facilitating the market entry of SIs (Roca and O'Sullivan, 2022; Ellwood et al., 2022). Meanwhile, given the nascent nature of SIs (Juntunen et al., 2019), the regulatory landscape for such innovations remains underdeveloped, inundated with partially defined guidelines and standards. Thus, while prior studies have underlined the potential of regulatory agencies to operate as intermediaries whose activities support and stimulate innovation (Goodman et al., 2017; Wiegmann et al., 2017; Kivimaa, 2014), there is still relatively little efforts to provide a settled argument on how regulatory agencies could capture integral role in fostering the commercialisation of SIs.

Nonetheless, we argue that the nascent nature of the SI field instead offers avenue for extensive collaborative efforts between regulatory agencies and sustainability-oriented firms towards co-creating bespoke regulatory framework and standards. In this regard, we submit the existing grey area of circumspective scholarly engagement on avenues to intensify regulatory intervention in the SI process is largely due to the tendency, or rather an uncertainty, that calls for regulatory focus on accelerating specific type of innovations could lead distortions in the market; a potential risk of the regulator picking winners and/or losers for the market economy. We therefore argue that this sentiment is very much insistent in the traditional practices and thinking about regulation, which is draped in a paradoxical, suboptimal neutral ground within the melded interaction between regulatory actions, markets, and the innovation landscapes (Kivimaa; 2014; Maggetti, 2009; Dewick and Miozzo, 2002). Yet, in the light of the centrality of regulatory activities to the viability and ubiquity of SI domains we submit that there is a need to intensify scholarly debates on the organizing schema of regulatory agencies with the intension to re-orient the traditional approach to conceptualising the role of regulation in innovation. Conceiving our conceptual treatment of the activities of regulatory agencies in the shadows of existing discourses on stakeholder roles in sustainability-oriented innovation process (such as stimulator, initiator, broker/mediator, concept refiner, legitimator, educator, context enabler and impact extender)

(Goodman et al., 2017), we capture regulatory review processes and activities in the SI field as one that is only *catalytic*. By catalytic we mean an abstraction of the role of regulatory agencies just as a catalyst, as defined within the natural science domains, intermediate and speed up the chemical reaction between substances without being permanently consumed in such reaction (Cantner and Vannuccini, 2018). In this respect, the activity patterns of regulatory agencies are perceived to be drawn toward defining the regulatory landscape for SIs, intervene, refine and ease the commercial transition of SIs but not to persist in order to allow the operation and competitiveness of the market economy at self-sustaining levels. The core argument we seek to advance is that orienting to a conceptual treatment of regulatory activities as catalytic to the SI process would help to stimulate the dynamic interactions between regulation and the innovation landscape through co-creation mechanisms in order to encourage sustainable innovation initiatives.

Our position, therefore, is not to suggest that regulatory agencies should directly impose commitments on firms to develop more SIs (Berrone et al., 2013). Rather, it is to conceive their role as one that reinforces efforts to developing SIs by defining regulatory structures for such new products and facilitating their market authorisation and commercial success. In this regard, our stance in the discourse on regulation is overtly situated in a view that conceives regulatory agencies as contributing to a web of stakeholder roles and relationships which is geared towards fostering a new paradigm of new product development that is targeted at meeting the pressing sustainability needs (Kivimaa, 2019; Wiegmann et al., 2017; Ketata et al., 2015). In this vein, our contributions in this paper to the literature on regulation and SIs is avowed in threefold. First, given our appreciation of the tendency that regulatory agencies may exert some inimical influence on innovation (Boakye et al., 2022; Hall et al., 2018), we draw attention to the potential to restructure regulation to systematically concentrate on innovation incentivising objectives. Specifically, we highlight on how regulatory standards and activities could be co-created with SI domains, influence the market as well as the strategic choices of innovating firms, in order to bring into fruition, the much-anticipated sustainable industrial revolution. Second, we take a firm position in this paper to advocate for regulatory intervention in the bid to foster

sustainable product innovations. This rather early stance helps to highlight, assess, and initiate enquiry into the relationships and independency between regulation and innovation in order to suggest measurable policy-oriented solutions that would help cement the much-needed sustainability transition. Third, as we embed our discussions in relevant debates on the role of regulation in innovation, we broaden the existing theoretical arrestation on regulatory activities by presenting it as a catalyst that could accelerate sustainable solutions to the existential socio-ecological and economic challenges. This understanding of regulation will there help set the common stage for future research to focus on identifying the temporal dynamics of when to acknowledge the impermanence of regulatory intervention policies in order to allow the market economy to control its selection patterns.

The remainder of the paper is organized as follows. We start by characterising SIs as emergent in the form of nascent industry; hence, inform how they may trigger unique regulatory response. Following this a brief discussion of the role of regulation in innovation is presented, after which our catalytic framework is submitted. The final section provides a general overview of our arguments and conclude by way of stimulating further empirical research.

Sustainable Innovations: A nascent industry

The central conceptualisation which foregrounds this study is rooted in the notion that SIs are at their *nascence* of development (Juntunen et al., 2019). By their nascence we mean SIs fall within technological domain that are at early stage of formation, and where “technologies, business models, and paths to success are elusive and rapidly changing” (Zuzul and Tripsas, 2020, p. 397). They therefore constitute new technological concept that tend to challenge existing dominant designs, regulatory codes and standards, but whose design concept remain under-defined, and product categories continue to shift (Gao and McDonald, 2022; Santos and Eisenhardt, 2009). Such innovations are often draped in complex overturn of existing product architecture and systemic arrangements such that they require extensive collaborative efforts and co-creation mechanisms to accelerate their widespread application and dominance (Juntunen et al., 2019; Weber et al., 2008).

In light these insights, we are of the view that recent the sustainability trajectory of innovation the innovation landscape neatly finds its locus of abstraction within the concept of nascence. The core set of definitive features that encapsulates the existing commitments to defining new ways of creating value through the development of novel products that address the pressing needs of climate change and socio-economic challenges (Porter and Kramer, 2011; Rennings 2000) falls within the domain of a nascent industry. Specifically, the precise definition for SIs remains elusive in the literature and the anticipated sustainability-changes to existing socio-technical systems continue to offer yet-to-be-defined relations and actions of both market and non-market stakeholders (Goodman et al., 2017; Driessen and Hillebrand, 2013), and their outputs continue to satisfy only niche markets (Nill and Kemp, 2009). The magnitude of technological change required to drive the sustainability transition is also conceived to present sustainable value propositions that may render the existing 'unsustainable' or regular innovations obsolete (Hu et al., 2019; Mariadoss et al., 2011; Nidumolu et al., 2009). This novel field of innovation thus yield a myriad new product development that continue to present uncertainty in the patterns of market interactions yet constitute a conceived paradigm of design architectures for creating value and capturing of competitive advantage in a sustainability-oriented world (Varadarajan, 2017; Berrone et al., 2013; Schiederig et al., 2012). This is to say that regardless of its ambiguity in market structures the centrality of SI in the re-constitution of the extant socio-technical and economic systems is well acknowledged, such that it proffers new modes of organizational survival (Hall et al., 2018; Berrone et al., 2013; Rennings, 2000).

On this basis, we observe that the efforts to infuse environmental and social considerations into existing design concepts, as well as broader organizational strategy, has come to shape contemporary management practices (Amankwah-Amoah and Syllias, 2020; Roxas and Coetzer, 2012; Schiederig et al., 2012). Despite the rather infant stage of development, the emerging trajectories in the innovation landscape nurturing sensitivity to ecological and social concerns is increasingly influencing conditions of purchases and consumption in the market selection environment (Amatulli, 2020; Berrone et al., 2013). The sustainability philosophy of the innovating firm is thus taking hold as a measure of

organizational legitimacy and survival (Thomas and Lamm, 2012). Nonetheless, much as this concise discussion sheds light on how that the established features of SIs analogously situated in nascent industries, we re-emphasize that this novel field of innovation could be robustly developed to finds absolute meaning through deliberate efforts to expedite their adoption and diffusion in the market (Datta et al., 2015; Slater and Mohr, 2006). This brings into view the reactive responses of regulatory agencies to such innovation fields (Gao and McDonald, 2022; Lettl et al., 2006). Market entry and survival is reposed in the strict action of these non-market agents as the emerging SI field face the aged-old challenge of the *valley of death* (VoD) (Khizar et al., 2022; Dean et al., 2022). The regulators' role in controlling and influencing the commercial success of such innovation would prove critical to mitigating such threat and help shape the competitive dynamics of the SIs landscape.

Understanding the role of regulatory agencies

Regulatory agencies are non-market stakeholders whose activities determine the transition of new products from the laboratory to the market. They are tasked with the responsibility of effectively conducting technical evaluations to ensure that product innovations conform with approved standards and safety requirements (Wiegmann and Roca, 2021; Olson, 2008; Rindova et al., 2005). Amongst these standards are the efficacy and safety concerns that need to be mitigated to protect public health as well as the challenges posed by market failure (Guidi et al., 2020; Prieger, 2002). Thus, a new product innovation is adjudged fit for commercialisation based on outcome of series of evaluations that ultimately result in the approval or refusal of innovation commercial authorisations (Polidoro, 2020; Sherman et al., 2017). More importantly, their role is in significant in mitigating the challenges resulting from the asymmetrically distributed nature of information within existing markets (Polidoro, 2020; Downer, 2011). As result, the activities of the regulatory agencies effectively shape the dynamics of market conditions to influence the success of innovations, as they signal product quality and safety to the market (Polidoro, 2020; Kessler and Chakrabarti, 1996). The speed at which new product are introduced to the commercial activities of the selection environment is therefore dependent on the

decisions elicited by the regulatory agencies (Chorniy et al., 2021; Polidoro, 2020). In this regard, the centrality of regulatory activities in the effective adoption of SIs is made apparent as they constitute the influential stakeholders of the now sustainability-oriented industry and innovation landscapes (Verbeke and Hutzschenreuter, 2021; Brunnermeier and Cohen, 2003; Dewick, and Miozzo, 2002).

Taking stock of the discussion so far, we present our argument that although regulatory evaluations are rendered a necessary condition to ensure innovations are safe for public use, their role in the innovation process would only be sufficient by re-conceiving them as providing enabling effect on innovation through the process of selecting out and expediting sustainable new products into the market (Gliedt et al., 2018). This is important because the creation and legitimization of new markets, or the radical transformation existing ones, and the definition of the basis of competition in the innovation landscape, through the processes of “rule-setting, rule-monitoring, and rule-enforcing” (Guidi et al., 2020, p. 6), is largely defined within the roles of the regulator (Wiegmann et al., 2017). Regulatory agencies are therefore not only perceived as watchdogs on the defensive stance of public health and safety, but also as institutions whose activities shape market perception, preferences, and innovation strategies of the firm (Boakye et al., 2022, Kivimaa, 2019). In this regard, regulatory policies, practices, and initiatives have the potential to translate into logical reactions from the ordered interactions between innovating firms, and the users of innovation output (Polidoro, 2020; Lee et al., 2010). In effect, a new dominant innovation output which is laced with the tenors of sustainability, or the adaptation the existing socio-technical systems, could be collaboratively established (Shao et al., 2021; Guidi et al., 2020; Kotler, 2011). A valuable essence of their role therefore is their ability to sense a need to address problematic conditions in the market and society at large and provide counter measures by nudging innovating firms to incorporate lasting solutions into new product design in order to render the innovation systems more resilient to socio-technical dynamics being driven towards sustainability (Sarpong et al., 2020).

As such, a well-defined regulatory policy that considers how the organizing structures that shape the decision-making process as well as the type of regulatory framework adopted to achieving sustainable outcomes of the market selection environment is much needed (Foucart and Li, 2021; Polidoro, 2020; Hillman et al., 2011). This also implies that a redefinition of the organizing principles and objectives regulatory agencies to accelerate the commercialisation of both emerging and existing SI output would trigger profound changes in the innovation landscape. Thus, while some notable regulatory effort has been made to providing enabling conditions that will boost sustainable Research and Development (R&D) intensity and innovation (Blind et al., 2017; Sarpong et al., 2022), we emphasised on role of regulation to fulfilling the commercial ends of the concomitant outputs. More importantly, the melded activities of regulatory agencies, be it standard setting or a direct evaluation of innovation output to ensure safety and quality (Boakye et al., 2022; Blind et al., 2017), need to encourage the diffusion of sustainable forms of innovations (Kivimaa, 2019). To this end, we draw attention to a need to establishing aligned intention of regulatory policies on social regulations that addresses sustainability concerns by creating competitive pressures that indirectly drives innovating firms to channel efforts towards developing SIs (Kivimaa, 2019; Blind, 2016; Lee et al., 2010)

Against this background, it worth acknowledging the intermediating role of regulatory agencies in the transitioning of SI output from the marginal to the mainstream of the innovation landscape (Gliedt et al., 2018). As Goodman et al. (2017) argued, the quest to establishing sustainable socio-technical systems require continuous renegotiation and collaboration across multiple stakeholders—including regulatory agencies. Thus, extending their role beyond the traditional legitimatisation of markets and product, channelling regulatory efforts to expediting the development and commercialisation of SIs is to be considered core in the quest to achieving sustainable transitions (Gliedt et al., 2018; Elzen et al., 2012)— and not an option. Regulatory policies that seek to create a momentum dominance of SI outputs, proactively refining such product and facilitating their widespread impact through widespread use can therefore be conceived to be catalyst to the sustainability shift in existing sociotechnical systems (Goodman et al., 2017; Kivimaa, 2014). This brings

thus into view the need to draw attention to how such direct action could be conceived and negotiated without unleashing the usual innovation hindering outcomes of (over)regulation (de Moraes, 2022; Aho, 2017) or even the tendency to distort the market economy. The central question we must address therefore is: What form must the catalytic action of regulatory policy take if we must co-optimize market dominance of SI and allow market economy to determine its competitive dynamics? In what follows, we present our catalytic framework of regulation to highlight on their role in accelerating SIs could be achieved.

Catalytic framework of regulation

A *catalyst* as described in the intellectual domains of natural sciences is a substance that accelerates the rate of a chemical reaction without itself becoming permanently involved in the reaction (Chintawar et al., 2021; Richardson, 2013). In other words, they are substances that take an active part in a reaction by introducing a less difficult path for molecules to flow but are not fully consumed in the reaction. The use of catalysts, however, is not to imply that uncatalyzed reactions cannot achieve expected equilibrium, rather it is to acknowledge that such reactions may tend to be immeasurably slow in process and may not yield desirable outcomes (Ramos De Dios, 2022; Twigg, 2018). More importantly in reactions such as ammonia oxidation where reaction conditions may give rise to different products a catalyst is required to give selectivity in oxidation to the wanted product. Thus, a catalyst does not only have the ability to actively engage in the process of triggering exponential rates of speed in a reaction, but also can be used to selectively change the rate of undesired reaction as well as the rate of a desired outcome (Twigg, 2018, p. 26). It is worth noting, however, that the time frame within which a catalyst keeps a sufficient level of active involvement and selectivity is of importance. As such the catalyst takes active part only long enough for the desired reaction to be complete.

In relating how a catalyst actively precipitates the rate of chemical reaction to a selective outcome within a temporarily sufficient span of time to the context of regulation, we are prompted to conceptualise anew the role of regulation through the core working principle of a catalyst. Our

argument here is that regulations can be used to propel the wheels of sustainability just as a catalyst accelerates the rate of chemical reaction. Thus, regulatory agencies by virtue of their ability to influence the flow of innovation and shape innovation strategies of the firm (Dedehayir et al., 2018; Backman et al., 2017), may play an instrumental role in selectively pushing forward eco-innovations by establishing less complex evaluation frameworks and commercial-inducing policies (Martínez-Noya and García-Canal, 2016; Kivimaa, 2014). We however continue to hold the view that the activation of such regulatory system should be viewed in the shadows of impermanence in order to avoid persistent interference in the selection patterns of the market economy. Catalytic regulation strategy leading to the acceleration of eco-innovation towards sustainable equilibriums in markets should therefore be weaved with the cognizance to pull back when the interventions achieve its objectives. We posit that such regulatory approach should be pursued by establishing a fine balance between designing regulatory frameworks that actively encourage the development of eco-innovations and at the same time define the life limits at which the interventions would be docked after triggering mass innovation activities towards sustainable ends. This would mean that in the mid to long run, selection of winners or losers would be autonomously decided by the active agents in the market-based selection environment.

On this analysis, although we acknowledge the numerous regulatory policies and innovations practices such university-industry collaboration and the provision financial support to help transition new product design towards commercial scale (Roca and O'Sullivan, 2022), our focus here is on the specific set regulatory activities that prompts rapid diffusion of SIs into the market which diminishing unsustainable. In this regard, the onus is relayed on the regulatory agencies who ensure technical safety and efficacy of the new product innovation to facility and expedite both the evaluation process of SIs and design stringent sustainability standards. Here, we are of the view that the power of regulatory agencies to operate as a brake to the velocity of the innovation process (McCarthy et al., 2010; Kessler and Chakrabarti, 1996), also implies that their activities can be designed to specifically accelerate the development and commercialisation of innovations. This support may be in the form of regulatory efforts to prioritising green innovation by enriching regulatory collaboration in sustainable R&D

initiatives (Kamguia et al., 2022; Muscio, et al., 2017), offering immediate support to sustainable new sustainable alternatives through their role as innovation intermediaries, and providing sustainability performance and standard compliance incentives. Highlighting on the ability of these non- exhaustive catalytic regulatory approach to shape perception of innovators to eliciting strategic responses that would drive sustainability transition, the present the following propositions.

Proposition 1: *Providing immediate support to new sustainable technological will trigger interest in the innovation landscape to adopt sustainability compliant technologies.*

Proposition 2: *Regulatory policies that stimulate green Research and Development projects would yield sustainability-oriented change new product design and development process.*

Proposition 3: *Regulatory activities that conscientizes the market about the need for sustainable product will the stimulate demand eco-innovation thereby driving firm investing in regular innovations to provide sustainable substitutes.*

Proposition 4: *Offering sustainability performance and standard compliance incentives will strengthen commitments to designing and producing sustainable technologies.*

Against this background, we piece together the discussions to emergently develop our framework in figure 1 which highlights on how catalytic regulation can intervene in the competitive dynamics of the existing innovation landscape by establishing a mechanism for innovating firms to exploit and explore SI trajectories. As depicted in the heuristic framework, the existing innovations landscape is characterised by two forms of innovations. On the one hand is regular innovations (RIs) which are draws in the existing competence and production system to meet the needs of the market (Reinhardt et al., 2018; Abernathy and Clark, 1993). Such innovations are however entrenched in the existing social-technical systems which are largely irresponsive to the changing dynamics of the market environment triggered by growing ecological challenges (Edmondson et al., 2019; McMeekin and Southerton, 2012). On the other hand, lies SIs which offer radically transformative ways for producing products that directly addresses the ecological concerns of the market (Edmondson et al., 2019). They may also be characterised by incremental improvement in the existing products by infusing issues of

sustainability into the product redesign concept or take the form a radically new innovation output (Kivima et al., 2019).

As the framework indicates, at the start of a catalytic regulation at time t the focus of the new product review process would be to create a conducive regulatory environment by designing flexible evaluation criteria and providing clear guidelines that would aid SI to undergo expedited evaluation process. Concurrently, regulatory efforts would also be geared at providing assurances of safety and quality, endorsing, and creating legitimacy for SI outputs. This approach would therefore serve as channel through which the valley of death (VoD) for SIs could be bridged (Roca and O'Sullivan, 2022; Mossberg, 2018). The regulatory practices and policies identified here are thus geared toward an intermediary role of accelerating the commercial transition of SIs. In effect, a wider boost in the in the development of sustainable product designs as a strategic response spurred by the anticipation of regulatory focus would be defined. At this stage the essence of regulation would be to design flexible and specific product evaluation criteria for SIs, secure both legislative and financial support sustainable product designs, establishing clear guidelines for eco-friendly innovations to meet regulatory standards and requirements, signally and assuring the market on safety and quality of SIs, and where direct technical evaluation of products are required, allocate resources to provide expedited review process for such innovations.

INSERT FIGURE 1 ABOUT HERE

On the contrary, RIs which do not infuse the issues of sustainability may initially struggle to exploit the catalytic regulation channel to bridge the VoD. The regulatory activities embedded in the new product review process would therefore be generally restrictive to the RIs. Consequently, such innovation would not have the utmost support of the regulation in influencing the market selection

decisions. This would signal to innovating firms to anticipate changes in the regulatory focus on sustainability issues thereby redirect their innovation efforts towards sustainable design concepts (Liao and Tsai, 2019). In other words, a catalytic regulation would encourage wide-spread adoption of SI output thereby triggering adaptation of existing technologies and create radical shifts in the trajectories of emerging ones. Therefore, with the urge to commercialise their innovation output to retain competitiveness and market survival, the innovating firm may eventually channel their resources to exploring SI domains. However, since there is the need to minimize regulatory influence on the market, at time t^* , a catalytic regulation is expected to culminate. At this point, the selection environment is also expected to have reached its maturation where it can be said to have found a self-sustaining equilibrium where the selection pattern would no longer require regulatory influence to select sustainable products. This market condition as already being experienced in industries where the new products design which require minimal externality on the natural ecology are able to compete on the basis of both price and performance (Viciunaite and Alfnes, 2020; Yang et al., 2019) lends empirical support to the proposed self-sustaining level. Consequently, the catalytic regulation initiative may at this stage be withdrawn to allow the market economy to operate.

Discussion and conclusion

The head-on clash between those whose priority is on the economic imperatives of product innovation and those who call for sustainability underlines the accepted conceptualisation of differential visions of the 'active' participant in the market and a 'passive' overseer of the selection environment. Held up in the shadows of possible imposition of preferences of the regulator on the market, this longstanding view of innovating firms as the legitimate and direct interactors in market exchange has continued to spark arguments about whether the regulatory agencies, as non-market stakeholders, should transition from passive 'agents' to 'actors' in the market selection environment (Partzsch, 2009). Furthering these discussions, we set out in this paper to offer an incisive (re)conception on how the role regulation in accelerating innovations can be conceived and operationalised within the sparring concerns about market competition. Specifically, we conceived the SI landscape as a nascent domain that require

deliberate stakeholder effort accelerate their commercial transitions and market success. We proposed that regulation simply needs to nudge the innovation landscape to design products that create inextricable blend of economic, social and environmental value creation (Verbeke and Hutzschenreuter, 2021; Gimenez et al., 2012). Thus, the radical industrial change that we seek to bring to fruition is implicated the ability of regulators to perceptively pursue their role as intervening to stimulate and speed up commercialisation of SIs. Highlighting their power to co-optimize their operational objective to protect public health and safety as well as stimulate innovation by driving the commercial success of SIs, we devised a heuristic framework, which draws on working principles of a catalyst in a chemical reaction, to depict how regulatory agencies could reorient innovation trajectories towards developing more sustainable solutions.

Against this background, the paper proposed a catalytic framework of regulation as a much-needed approach to refining our understanding of regulation, and to advance discussions on how regulation could propel the sustainable industrial revolution. This mechanism through which regulation nudges the innovation landscape to redirect activities towards developing SIs, as depict on our framework, strikes a fine distinction between regular and SIs but shows an important similarity. Here, both identified forms of innovation are conceived to undergo regulatory evaluations to gain the authorisation to commercialise or must satisfy stringent regulatory standards and requirements. In this regard, the framework depicts how a catalytic approach to regulation may help refine, accelerate the market authorisation, enable favourable the selection environment (Goodman et al., 2017) and specifically focus on eliminating the existential threats of the valley of death to remove dead-ends in SIs (Koch-Ørvad, 2019; Neves and Franco, 2018). More importantly, we elaborated on the reconfiguration of the tenets of regulation to adopt a catalytic approach that focuses on easing the rules and standards of evaluations as well as actively influencing the responses of the market selection environment. In this regard, an understanding of how regulation could provide a support mechanism that would encourage innovating firms to logically adapt to the sustainable trends in order to achieve success on the market is provided. As such, although the objective is to create market dominance for SI by shaping responses

of both innovating firms and consumers, the framework emphasises on the need to design catalytic regulation with a systematic rationale for discontinuity.

Our paper has two main policy implications. First, we advocate for regulatory initiative that seek to providing the enabling environment for SIs to thrive to directly some considerable attention to the demand conditions for such outputs. As such regulatory policies ought to be driven towards intermediating the in the diffusion of SI output onto the market by equally providing incentive for the end-users as the 'protagonists of commercial exchange' (Callon, 2021, Nielsen et al., 2016) to actively engage in the sustainability drive. Second, as we emphasise the innovating firms' survival in the market being implicated in the activities of regulatory agencies, we underly the importance of regulatory policies to encourage innovating firms to anticipate and design responses changing patterns of regulatory focus in order to pre-empt potential lags commercialization that may results from lack of cognizance of regulatory the catalytic conditions provided through regulation. This also requires conscious efforts by policy makers to minimize regulatory uncertainty by making logical changes in regulatory policies and procedures that allow innovating firm to explore sustainable alternatives.

The arguments we have submitted also yield intuitive basis to inform strategic thinking about ways innovating firms could capture value from SIs, precisely by making deliberate efforts to align innovation output with the interest and preferences of regulation. Thus, new product innovations could be designed to internalise the ideals and tenors of sustainability in order to effectively exploit the commercialisation channels established by a catalytic regulatory system. In addition, we highlight on how the socio-ecological concerns that dominates the narratives of today, and potentially that of tomorrow, could be carved into reality through the active intervention of regulation. We emphasise on the ability of regulation to influence and redirect the patterns of innovation by creating expectation regarding specific design features or market niche that are likely to be successful on the market thereby driving innovating firms towards developing products that incorporates such features. Furthermore, although our catalytic conceptualisation of the role of regulation in fostering innovations is one that

calls on deliberately efforts to establish the dominance of SIs, we acknowledge that allowing the choices and decisions that define competition in the market is a crucial aspect of such emergence. Thus, the modes of selection in the market economy which offer pareto optimality continue to bind the temporal dimension of the intervention tools that a catalytic regulation may adopt.

This conceptual endeavour further opens many avenues for future empirical research. Specifically, we relinquish two key concerns into the realm of future research. First, a keen focus on transitioning the existing socio-technical system towards a more sustainable end may not always be ideal as some product designs may need to emerge in the form regular innovations and incrementally mutate into sustainably forms by reacting with the conditions of the selection environment (Calabrese et al., 2005; Debruyne et al, 2002). Such innovations may be the next technological breakthroughs that a catalytic regulation that focuses on SI would not provide the channels to help bridge the VoD; hence their benefits may never be realised. The contention now is how to design regulation in ways that do not lead the demise of such innovation but offer commitments to commercialise regular innovations while contemporaneously nudging them to make sustainable incremental in their core design concepts. Second, although we emphasise that our catalytic regulation should discontinue after reaching sustainable levels, the question about when and how to determine this ideal withdrawal time to remains answered. More so, there is the tendency of such catalytic regulatory policy depleting in terms of its effectiveness to due to risk of regulatory capture. We therefore recommend future research to draw on retrospective study of how dominant design concepts have historically been established, as well as existential cases on regulatory capture, to offer some insights about how catalytic regulation could be shielded from influences of the innovating firms, as well as determine the span of time within which a catalytic regulation would be sufficient and can be withdrawn.

In conclusion, the well-established literature on regulation and innovation has made progress in acknowledging the role of regulation in promoting innovation. However, the contention has been on whether to allow regulation to actively engage in the market economy, particularly when the SI

landscape is at its nascence where developing bespoke regulatory framework has proved challenging. Yet, given the importance and urgency to address the threats posed by climate change and socio-economic challenges, calling for regulatory intervention to establish market dominance for SI is of utmost importance. Thus, this paper has offered a new conceptualisation of regulation which constitutes a significant step in understanding how regulation could be designed to stimulate SIs without permanently interfering in the selection patterns of the market economy.

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