Green growth or degrowth? Evaluating the potential of technology for sustainability

Abstract

The raging debate between green growth and degrowth continues. Technology is a focal point in this debate as the advocates of green growth and degrowth have contradictory views on the roles and impacts of technology on environment and society. Green growth advocates believe that technology can allow indefinite growth while simultaneously ensuring environmental and societal sustainability, whereas the degrowth advocates argue that technological progress cannot allow indefinite growth. These views are largely opinion based rather than informed by objective and systematic analyses because comprehensive tools to evaluate the roles and impacts of technology on environment and society do not yet exist. This paper develops a much-needed framework to comprehensively evaluate the roles of technology on environment and society by analysing the interactions among the dimensions of technology, environment, economy and society. Key parameters that characterise technology are proposed for its evaluation and the policy implications of technological evaluations are examined. Finally, potential future research directions are explored. The technological evaluation approach proposed in this paper has a potential to significantly advance the green growth versus degrowth debate.

Keywords: technology; green growth; degrowth; sustainability; policy; societal transition

JEL O330; JEL A12; JEL I31

1. Introduction

Green growth and degrowth are two contradictory economic paradigms and the debate between these two paradigms continues. The Organisation for Economic Co-operation and Development (OECD) envisions green growth as a means of "fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies" (OECD, 2019). Green growth therefore assumes that economic growth can be maintained indefinitely while also sustaining natural assets at the same time. Innovation and technology are implicitly assumed to be the instruments to achieve continuous economic growth while sustaining natural resources. Degrowth, on the other hand, argues that it is impossible to achieve indefinite economic growth in a finite world given the ecological boundaries (Boonstra and Joosse, 2013; Buch-Hansen, 2018). The degrowth paradigm implicitly assumes that no degree of technological progress can indefinitely sustain economic growth and environmental assets simultaneously.

Technology is at the heart of green growth versus degrowth debate as technological progress and innovations are assumed to be the main drivers of green growth. Therefore, it is very important to evaluate technology for its potential to achieve green growth indefinitely. A crucial question that both green growth and degrowth advocates need to address, and which still has not yet received sufficient attention by the research community is: how can the potential of technology to maintain long term green growth and create a sustainable society be objectively evaluated? An attempt to answer this question has been made here. This paper contributes in advancing the green growth versus degrowth debate by developing an approach to evaluate technology for its capability in maintaining long term green growth and creating a sustainable society. Furthermore, this paper stimulates discussions on the public policy question: how to decide whether any given technology should be advanced and implemented or phased out?

This paper is organised as follows. First, growth versus degrowth debate and the roles of technology in this debate are explored in the context of sustainability (Section 2). Then, complex interactions among technology, environment, economy and society are analysed to create a framework that enables evaluation of technology qualitatively and quantitatively (Section 3). Based on this analysis, key parameters to evaluate technology for its potential to create a sustainable society and advance growth versus degrowth debate are proposed (Section 4). An approach to optimise technological design in terms of proposed parameters is outlined, followed by discussions on policy implications of technological design and future research directions (Section 5). Finally, conclusions are presented in Section 6.

2. Green growth, degrowth, technology and sustainable society

The ongoing debate between green growth versus degrowth has a long history and may be considered a new version of Cornucopians versus (neo-)Malthusians debate. The cornucopian perspective is that the world is a place of infinite resources and the human ability to adapt and innovate is generally able to compensate for apparent shortages of any particular natural resources. Consequently, Cornucopians have optimistic view on the potential of technological advancement (Laugs and Moll, 2017) which is similar to the views of green growth advocates. Malthusians, on the other hand, have a perspective that there are severe limits to growth and resource use, and an unchecked growth will exceed the earth's carrying capacity thereby leading to disasters (Chenoweth and Feitelson, 2005). Therefore, the Mathusian view implicitly assumes that technology cannot sustain economic and population growth indefinitely. While there may not be a consensus about the meaning of the term "Technology" (Lawson, 2008), this paper uses the term "technology" to refer to the macro view of "technological system". Leoncini (1998) utilises a holistic concept of technological system to describe a system that constitutes of four main building blocks, namely, a hard core of technological and scientific knowledge, a constellation of technical systems, the market environment, and the institutional interface (Leoncini, 1998).

The cornucopian perspective on the potential of technology is opposite to that of Malthusian perspective. While the Cornucopians perceive technology as an ultimate solution, the Malthusians acknowledge the limitations of technology by implicitly assuming that technology cannot solve the resource scarcity problems caused by indefinite growth. This also holds true for green growth versus degrowth debate. Green growth views technology – particularly clean technology, information and communication technology, and renewable energy – as a tool to sustain indefinite growth. On the contrary, degrowth argues for slowing down the growth process and implicitly assumes that technological progress and innovation cannot sustain indefinite growth.

Similar to green growth and degrowth discourses, impacts of technology on environment and larger society have been viewed positively as well as negatively by the contrasting doctrines of technological optimism and insidiousness of technology (Whyte *et al.*, 2017). Technological optimism argues for green growth or eco-growth whereas insidiousness of technology argues for degrowth. The basic principle of technological optimism is that economic growth and environmental sustainability can both be simultaneously achieved through technology, and an argument that information and communication technology can help achieve this (Perez, 2016) is one example. Likewise, numerical modelling (Nasrollahi *et al.*, 2020) has shown positive relationship between sustainability and technology to further build the case for technological optimism. In contrast, it has been pointed out that technological optimism is not based on explicit conceptual assessment, and the factual role of technology and its beneficiaries are almost never clearly addressed in sustainability discussion (Gonella *et al.*, 2019). Similarly, Keary (2016) posits that the notion that technological change can solve environmental problems is based on a flawed assumption that technological innovations are predictable. An example is the unfulfilled promise of carbon capture and storage technology, where inflated blind techno-optimism which ignored many risks and uncertainties led to a sense of technological disillusion in Japan (Asayama and Ishii, 2017). It has also been argued that technological optimism does not account for the ambivalences of technology and its unintended consequences (Grunwald, 2018).

Technology may be an ambivalent dimension (Feenberg, 1990) in and of itself which can either support or inhibit the establishment of a sustainable society. For instance, a group of scientists (Vinuesa *et al.*, 2020) from various fields have expressed that artificial intelligence technology in particular can have both positive and negative impacts on achieving the sustainable development goals. Given the central roles of technology in sustainability and green growth versus degrowth discourses, frameworks and tools to evaluate impacts of technology are crucial and warrant greater attentions from the research community. This paper contends that until robust scientific methods, frameworks and tools are developed to evaluate the role of technology on environment and society, no progress on green growth versus debate can be made. While framework for attitudes towards technology in the context of ecological economics has been developed (Kerschne and Ehlers, 2016), frameworks based on empirical evidence that evaluate the roles of technology on environment and society are still lacking. Hence, an attempt is made here to develop a framework to evaluate the role of technology on environment and society by analysing the interactions among technology, environment, economy and society (see Section 3). The framework seeks to provide a much needed tool (Gonella *et al.*, 2019) to conduct broad and long-term assessments of technological sustainability. The main aim is to create a framework that evaluates technology objectively, precisely and empirically rather than subjectively. Debates such as technological optimism versus insidiousness of technology and green growth versus degrowth have largely been driven by opinions and theories rather than by objective evaluations or empirical studies. Examples include justifying degrowth based on critical social theory (Sandberg et al. 2019) or advocating for green growth based on potential of information and communication technology (Perez, 2016).

Another aim of the framework developed here is to stimulate a discussion on standard tools and methodology to evaluate technology. In addition to significantly contributing towards leveraging technology for global sustainability, standardised methodology to evaluate technology will also greatly advance the green growth versus degrowth debate. It has been pointed out that the advocates of degrowth need to develop a clearer position regarding expectations from technological progress (Grunwald, 2018), and the framework provided here could help them develop such position.

3. Interaction among technology, environment, economy and society

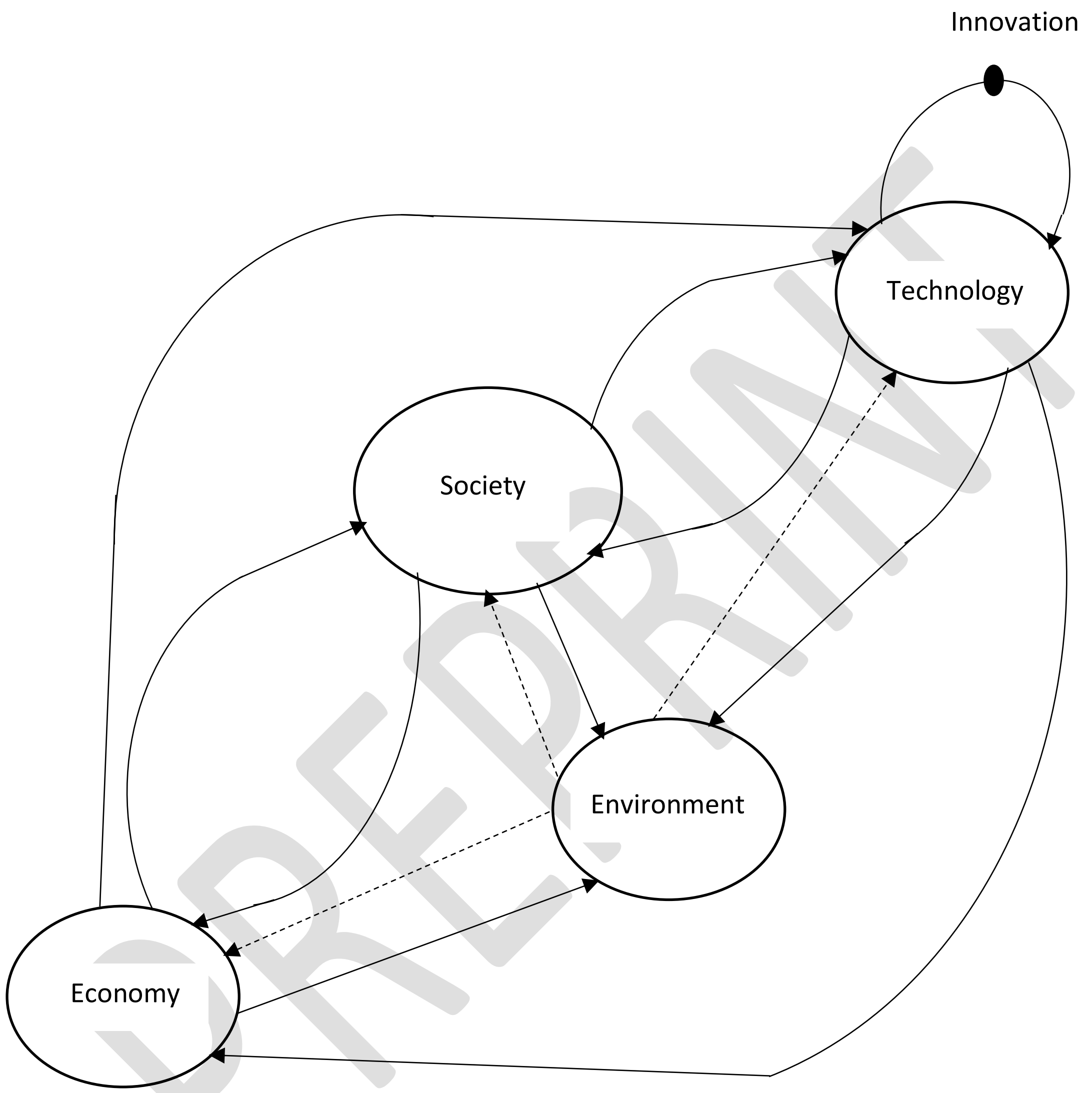
This section analyses interactions among four dimensions: technology, environment, economy and society, in order to develop a conceptual framework to evaluate technology. Technology is a very complex dimension that interacts closely with almost all aspects of human society and therefore its impacts cannot be evaluated by merely considering environment in isolation while excluding economics and societal aspects. Rather, complex interactions among all four dimensions mentioned above need to be analysed to assess technological impacts and the trade-offs created by technology. There are few approaches to quantify the impacts of technology on environment such as STIRPAT (Stochastic Impacts by Regression on Population, Affluence and Technology) and Decomposition Analysis (Vélez-Henao *et al.*, 2019), however, these approaches operate in a narrow boundary and do not take societal aspects into account. The framework provided here could therefore supplement existing approaches in evaluating technology from multiple perspectives. Furthermore, the analysis conducted in this section can be used for both qualitative and quantitative evaluations of technology as it may not be possible to quantify every technological impact. Quantitative models typically have an implicit assumption that technological change, which is strongly affected by human and societal behaviours, can be rationally and mathematically modelled. However, humans are not supercomputers that are constantly computing for optimal decisions and the notion that humans are rational agents that only make rational decisions have been challenged by many scholars (Kahneman, 1994; Mercure *et al*., 2016). Therefore, the analysis of interactions among technology, environment, economy and society conducted below allows for building both qualitative and quantitative models.

Economic agenda such as maximising productivity to increase profit drive technological innovations which have environmental impacts. These impacts lead to environmental policy interventions which can constrain or incentivise path of technological progress (Jaffe *et al.*, 2003). A study in China (Guo *et al.*, 2017) has concluded that environmental regulations positively influence technological innovations, which in turn have positive impact on regional green growth performance. However, technology enabled resource overuse also leads to inequality. As argued by Mirza *et al.* (2019), access to technology, or the lack thereof, may be a mechanism that fuels resource degradation and consequently push most vulnerable members of society into a poverty trap. This is because the rich will have access to technologies that enable them to maintain their wealth at the expense of the poor, whereas poor will not have access to the technologies. There exists a nexus among economy, environment, inequality and quality of life. For example, environmental toxicity has disproportionate effects on low income groups in US cities (Sampson, 2017), and Drupp *et al.* (2018) have concluded that economic inequality affects the value that society attaches to natural capital. According to them, reduction in economic inequality increases the value that society places on natural capital, and therefore, valuation of environmental goods and distribution of incomes should be studied simultaneously.

Technology and society also have co-dependent relationship with each other and as argued by Safarzyńska and van den Bergh (2017), technological change results from interactions within and between consumer and producer populations. By giving an example of smartphone industry, they point out how brand loyalty and social comparisons make many consumers frequently upgrade their phones thereby driving technological innovation in smartphone industry. This implies that income inequality and social status affect consumption pattern (agent heterogeneity), which in turn affect both the economy and the environment. These show intimate relationships among technological, environmental, economic and societal dimensions. Therefore, it is necessary to analyse the complex interactions among these dimensions to develop a framework which evaluates the roles of technology on environment on society. Consequently, a framework that evaluates technology should take into account both societal parameters – such as quality of life and income inequality – and environmental parameters such as natural capital depletion.

Basic overview of interactions among technology, environment, economy and society is represented in Figure 1. This figure is created to identify key parameters that can be utilised to evaluate technology (see Section 4). This schematic diagram (Figure 1) can also act as a template to build quantitative models such as system dynamics models or agent based models. Furthermore, this diagram may also be utilised for qualitative analysis. It is noteworthy that the template of interaction shown in Figure 1 is just one example intended to initiate broader discussions on the topic and many similar templates could be created. Figure 1 shows that the three pairs – society and technology, society and economy, and economy and technology – reinforce one another and are co-dependent. Additionally, technology is shown to reinforce itself through innovation. This is because a technology can aid in the development of another new technology and the technological dimension is inherently self-enforcing. Figure 1 also shows that environment is more strongly impacted by economy, technology and society, whereas the reverse impacts of environment on them are shown to be relatively weak (represented by dashed arrows in Figure 1) in modern times. This is because technology has allowed humans (particularly the rich) to largely "control" the environment over the past few centuries. However, technological advancement has also led to global environmental problems such as climate change, pollution and depletion of natural resources, and to what extent technology can solve or control these problems is debatable. It may be noted here that Figure 1 is presented to illustrate the need for system thinking approach as technology, environment, economy and society are intimately connected and cannot be studied in isolation.

Figure 1: Interactions among technology, environment, economy and society



Once the template of interactions among economy, environment, technology and society is developed as shown in Figure 1, it is necessary to identify parameters that characterise these dimensions and their interactions. The parameters need be objectively verifiable so that technology can be empirically, accurately and objectively evaluated for its role in environment and society. Key economic, environmental, technological and societal parameters are identified in the following section so that technology can be evaluated in terms of these parameters.

4. Parameters for technology evaluation

This section identifies key parameters that characterise the interactions among technology, environment, economy and society. The effects of technology on these parameters can evaluate the roles of technology on environment and society. Comprehensive evaluation of technology is a very important step toward understanding whether technology can sustain economic growth indefinitely and therefore an attempt to create a framework for holistic evaluation of technology is made in this paper. There are only very few literatures that evaluate the roles and impacts of technology on environment, economy and society holistically, with most available literatures isolating technological effects on economy (Dinçer *et al.*, 2019; Link, 1993) or environment (Munir and Ameer, 2018). Comprehensive framework to assess the roles of technology on environment, economy and society holistically has not yet been developed to the knowledge of the author. Therefore, key parameters necessary for such framework are identified in Table 1. Potential indicators that can be utilised to quantitatively characterise the identified parameters are also presented. It may be noted here that these parameters are not an exhaustive list but a starting point for broader discussions on this topic.

Table 1: Parameters to assess technology and potential quantitative indicators

Dimensions	**Assessment Parameters**	**Potential Quantitative Indicators**
Society	Quality of life, income inequality, consumption pattern, access to natural resources and technology, violent conflict	Human Development Index (HDI), Sustainable HDI, Gini Index, consumption rates, water footprint, penetration rate etc.
Environment	Climate change, natural capital depletion rates, pollution	Atmospheric CO_2 emissions, global surface temperature, global sea ice extent, global precipitation anomaly, global solar irradiance, natural capital depletion rates, reserve to production ratios, metrics for local air, land and water pollution etc.
Economy	Gross Domestic Product (GDP), unemployment rates	GDP, unemployment rates etc.
Technological	Efficiency, ease of adoption and diffusion, level of modularity, decoupling potential	Efficiency, potential change on energy-GDP elasticity etc.

Quantifying potential effects of a technology on the assessment parameters (Table 1) may be the most precise approach to evaluate its impacts and analyse the trade-offs caused by the technology. Therefore, indicators that can numerically measure the technological effects on the parameters are identified wherever possible (Table 1). In cases where the effects of technology on the parameters cannot be directly quantified, proxy numerical indicators are proposed. However, quantification may not be possible in all cases and qualitative evaluation of technology may have to be conducted. This can be done based on interaction models such as Figure 1. The parameters and the indicators to quantitatively characterise them are discussed below:

4.1. Societal dimension

As shown in Table 1, societal dimensions could be characterised by five parameters, namely, quality of life, income inequality, access to natural resources and technology, consumption pattern and violent conflict. Quality of life may be quantifiably measured using Human Development Index (HDI) which evaluates human development across three indicators, i.e., life expectancy, adult literacy and adjusted gross development product (Anand and Sen, 1994). However, it has been pointed out that HDI fails to include ecological and sustainability concerns (Sagar and Najam, 1998; Biggeri and Mauro, 2018; Doris *et al.*, 2020) and more comprehensive indicators for measuring quality of life that include sustainability and other aspects of well-being may be needed. Sustainable HDI (SHDI) proposed by Biggeri and Mauro (2018) may therefore be utilised to measure quality of life as the SHDI contains two additional indicators, freedom and environment, in addition to the three indicators considered by traditional HDI.

Another societal parameter is income inequality which can be quantitatively measured by Gini index. The Gini index measures the degree of individual or household income inequality with the value of zero representing perfect equality and 100 representing perfect inequality. Consumption pattern, which is another parameter, may be numerically measured by total primary energy consumption. Other indicators to measure consumption pattern could be consumption rates of non-renewable energy sources, water footprint et cetera.

The remaining two societal parameters, access to natural resources and technology and violent conflict are highly intertwined. Unequal access to natural resources and environmental changes have been linked with violent conflicts (Bernauer *et al.*, 2012) and it may be argued that most violent conflicts are results of unequal access to opportunities, natural resources and technology. Total number of violent conflicts per year due to unequal access may be utilised to measure the parameter violent conflict. Likewise, penetration rate of a given technology may be used as a proxy indicator to objectively measure access to that technology.

Roles and impacts of technology on the societal parameters can be numerically evaluated once the all the societal parameters are quantified. Mathematically, technological impact on society (T_s) may be expressed as a function: $T_s = f(Q, E, C, A, V)$, where Q, E, C, A, V are quantitative measures of quality of life, income inequality, consumption pattern, access to natural resources and technology, and violent conflict respectively. The exact mathematical expression for T_s depends on indicators chosen to quantitatively measure Q, E, C, A and V, and while indicators described above are potential candidates, further fine-tuning may be carried out on case by case basis. Qualitatively, technology should improve quality of life, reduce income inequality, reduce consumption pattern, improve equal access to natural resources and technology, and finally, reduce violent conflict. Therefore, technology meeting these conditions should have high numerical value for T_s and the technology which does not meet these conditions should have low T_s value. Consequently, T_s should have positive correlation with numerical indicators characterising quality of life and equal access to natural resources and technology, whereas, T_s should have negative correlation with numerical indicators characterising income inequality, increased consumption pattern and violent conflict. Thus, technological impacts on society can be qualitatively or quantitively evaluated.

4.2. Environmental dimension

Environmental dimension may be characterised by three parameters to evaluate the impacts of technology on environment. These three parameters are: climate change, natural capital depletion rates and pollution (Table 1). Potential quantitative indicators for climate change could be atmospheric CO_2 concentration, global surface temperature, global sea ice extent, global mean sea level, global precipitation anomaly and possibly total solar irradiance (Bhargawa and Singh, 2019). Likewise, potential quantitative indicators for natural capital depletion rates could be reserves to production ratios of non-renewable energy resources, rare earth minerals et cetera. Finally, qualitative and quantitative indicators for pollution could be based on life cycle analysis and environmental impact analysis of the technology. Local air, water and land pollution metrics also should be considered. After quantitative indicators for assessment parameters of environmental dimension are ascertained, technological impact on environment (T_e) may be mathematically expressed as a function of the parameters as: $T_e = f(C_c, D, P)$, where C_c, D and P are quantitative indicators for climate change, natural capital depletion rates and pollution respectively. The exact mathematical equation for T_e may depend on the technology being assessed and therefore may change on a case by case basis.

Although there may not exist a universal mathematical expression for T_e in terms of the environmental assessment parameters, it can be stated that impacts of technology should reduce climate change, natural capital depletion rates and pollution. This normative approach can also be utilised for qualitative evaluation of technological impacts on environment in cases where quantitative evaluation is not possible. Also, the technology meeting the above criteria should have high T_e value whereas the technology not meeting it should have low value. Consequently, T_e should have negative correlation with numerical indicators characterising increase in climate change, natural capital depletion rate and pollution.

4.3. Economic dimension

The assessment parameters for economy are chosen as GDP and unemployment rate which are numerical indicators in themselves. Therefore, impact of technology on economy (T_y) can be mathematically expressed as a function, $T_y = f(GDP, U)$, where U is unemployment rate. For qualitative assessment, technology should increase GDP and reduce unemployment rate, and quantitatively, T_y should increase with GDP and decrease with unemployment rate.

4.4. Technological dimension

Four assessment parameters are identified to evaluate technological dimensions, viz., efficiency, ease of adoption and diffusion, level of modularity and decoupling potential. Efficiency may refer to energy efficiency, production efficiency or some other technical efficiency characterising the performance of a technology in a case by case basis. Since efficiency is a quantitative parameter, it allows for objective and precise measurement of technological impact. Another parameter is related to technology adoption and diffusion, which has been considered as one of the key factors in transitioning to a sustainable society (Mercure *et al.*, 2016) as a technology that has higher ease of adoption and diffusion is likely to have higher impacts. Several approaches to quantitatively evaluate adoption and diffusion of technology have been described by Mercure *et al.* (2016).

Another assessment parameter for technological dimension is level or degree of modularity. As argued by Wilson *et al.* (2020), small-scale granular (or modular) technology offers higher potential of efficiency gains, faster diffusion, lower investment risk, faster learning and faster decarbonisation. Quantifiable indicators for level of modularity could depend on case by case basis for product modularity and process modularity (Modrak and Soltysova, 2018). The final assessment parameter for technological dimension is decoupling potential of technology in terms of decoupling economic growth and consumption of energy and resources. The green growth discourse which dominates current policy agenda is based on the assumption that decoupling environmental pressures from GDP could permit indefinite economic growth (Hernandez *et al.*, 2020). Therefore, decoupling potential will help evaluate the green growth discourse. Proxy quantitative indicator to measure decoupling potential could be calculating the potential energy-GDP elasticity (Burke and Csereklyei, 2016) change caused by the technology under evaluation.

After choosing all the quantifiable indicators, impact of technology on technological dimension (T_t) can be expressed as a mathematical function as: $T_t = f(\eta, E_a, M, D_p)$, where η is efficiency, E_a is ease of adoption and diffusion, M is level of modularity and D_p decoupling potential. For both qualitative and quantitative analysis, technology should increase efficiency, have high ease of adoption and diffusion, high level of modularity and high decoupling potential.

5. Discussions

This section presents an approach to optimise technological design based on the assessment parameters (Section 4), discusses the implications of evaluating technology and sets out research agenda for future research.

5.1. Optimising technological design

The aggregated impacts of technology on the four dimensions, namely, society, environment, economy and technology are mathematically characterised as T_s , T_e , T_y and T_t respectively in Section 4. Since higher numerical values of these terms indicate relatively more positive impacts and lower values indicate relatively less positive (or even negative) impacts, overall impact of technology (T) may be expressed as a function as: $T = f(T_s , T_e , T_y , T_t)$, where the mathematical function should be chosen in such a way that higher values of T represents more positive impacts and lower values represent less positive impacts. In this way, designing process of any technology can be viewed as an optimisation problem where the value of T is maximised. It may be noted here that the numerical value of T represents an aggregated estimate of impacts of technology that accounts for all the four dimensions discussed in Section 4, i.e., societal, environmental, economic and technological.

It is noteworthy that numerical optimisation may not always be possible for evaluating and designing technology given the complexity of interactions among different dimensions. Complexity increases as the interactions among assessment parameters (see Table 1) increases for a given technology. For instance, a technology that increases GDP (economic dimension parameter) could improve quality of life (societal dimension parameter) but it may also increase natural capital depletion (environmental dimension parameter) and income inequality (societal dimension parameter) – particularly if the considered technology is accessible only to rich people (another societal dimension parameter). Developing mathematical relationships for all the assessment parameters listed in Table 1 may not always be practical and computationally feasible for technology evaluation. Furthermore, the trade-offs created by a technology on the parameters are also not always obvious. For instance, normative propositions (or value judgements) that technology should have high ease of adoption and diffusion and high level of modularity have been made while discussing parameters for technological dimension (see Section 4.4). This is because both the assessment parameters – level of modularity and ease of adoption and diffusion – are argued to have great potential for sustainable transition (Mercure *et al.*, 2016; Wilson *et al.*, 2020). However, high level of modularity and high ease of adoption and diffusion can also create technological lock-in effects (Mercure *et al.*, 2016) where status quo is maintained and transitions to sustainability does not happen. Since a given assessment parameter can have positive, as well as negative impacts, quantitative approach may not be possible in some scenarios. Moreover, there can be cases where there are no clear dependant and independent variables for mathematical formulations, which may further limit numerical modelling. This can happen if technology cannot be mathematically defined in terms of other parameters (either dependant or independent variables) because of the complex interrelationships of technology (see Figure 1). Therefore, qualitative analyses to design, optimise and evaluate technology may also be needed to supplement quantitative approaches. Approaches to evaluate quantitative aggregates as T_s , T_e , T_y and T_t that assess the impacts of technology for each dimension are presented in this paper and similar approaches are also needed for aggregated qualitative assessments. Framework for such qualitative assessments is beyond the scope of this paper and is a limitation of this study.

5.2. Policy implications

Evaluation of technology using the approach described above will help set reasonable and rational expectations from technology which can have several policy implications. Firstly, broad evaluation of technology in general will advance the green growth versus degrowth debate and help decide whether policy agenda should be underpinned by green growth or degrowth discourse. Currently, international organisations such as United Nations and OECD have adopted green growth policy without critical evaluation of technology. Secondly, evaluation of technology will help guide the direction of technological advancement and evolution. It will allow for technological progress to be in consonant with environmental and societal sustainability by supporting the systematic decision-making process on whether to promote, discourage or ban a given technology.

Regulatory and policy decisions on impacts of a technology on environment and society need to be informed by rigorous evaluation of technology under consideration, as not doing so can have unintended consequences. For instance, Čavoški (2017) argued that European Union's overriding interest in regulating CO_2 emissions from vehicles led it to incentivise diesel technology which had unintended consequence of high level of air pollution. Also, current innovation systems are largely guided by institutions that primarily reflect the goals of the powerful rather than those of impoverished, marginalized, and future populations (Anadon *et al.*, 2016). Consequently, innovations are not aligned with the goals of sustainability. In this context, rigorous evaluation of technology using the approach presented in this paper can help in guiding and deploying technologies that can lead to sustainable societal transition.

Systematic and rigorous evaluation of technology based on qualitative as well as quantitative tools – for which this paper is a preliminary step – will support policy decisions regarding which technology to promote, which to discourage, ban or phase out. This will guide technological innovations in such a way that all the technology assessment parameters (Table 1) are maintained at optimal levels in order to create a sustainable and equitable society.

5.3. Future research directions

Evaluation of technology may be considered a "wicked problem" because of its complex interactions with environment, society and economy. This is one reason why the roles and impacts of technology have been endlessly debated between the green growth camp and the degrowth camp with their contradicting views on technology. Another reason is that the views of scientists and researchers regarding the roles and impacts of technology are primarily based on subjective opinions rather than on rigorous scientific analyses and empirical studies, mainly because there are no robust scientific assessment tools for technology. In this context, more research is needed to develop tools and techniques to evaluate broad impacts of technology on environment and society. Five important research themes and questions that need to be addressed are as enumerated. 1) How can the aggregated roles and impacts of technology be evaluated qualitatively? While this paper provides a quantitative framework for estimation of aggregated effects of technology as a numerical parameter T (see Section 5.1), similar conceptual framework for qualitative evaluation is lacking. 2) How should technological advancement be guided? Or should technology be allowed to progress organically without conscious human intervention? 3) Is full decoupling between economic growth and energy and resources consumption possible by technological intervention? If not, what degree of decoupling is possible and is it sufficient to allow indefinite economic growth while ensuring sustainability? 4) Circular economy has been viewed as an important approach to minimise harmful environmental impacts of economic growth through resource sharing and recycling. How to evaluate a potential of a technology to disrupt or enable circular economy? Disruption can happen, for example, if a new technology makes extraction of raw materials cheaper than recycling. Such technology will discourage recycling, and while this may produce temporary economic benefits, it will be catastrophic to environment in the long run. On a more general level, how to ensure that a disruptive technology always have positive environmental and societal impacts? 5) How can equality in access to technology be achieved? If advanced technologies are only accessible to the rich and powerful, violent conflicts that jeopardise societal stability are bound to happen.

In addition to addressing the broader questions mentioned above, further research is also necessary to enhance the framework developed in this paper to formulate robust tools for technological evaluation. Modelling equations need to be developed based on the mathematical functions suggested in Section 4 and Section 5.1. This will allow the application of quantitative tools such as system dynamics or agent-based modelling to estimate the value of T (see Section 5.1) for technology evaluation.

6. Conclusions

Potential roles and impacts of technology on environment and society have been a subject of great debate with arguments for technology mediated green growth as well as for degrowth that is based on principles of insidiousness of technology (or Malthusian ideas). However, comprehensive tools to evaluate the roles of technology still do not exist and this paper is a preliminary step towards creating such tools as it develops an approach to evaluate technology holistically. Key parameters to evaluate roles of technology on environment and society are identified here based on interactions among technology, environment, economy and society. A quantitative framework for this evaluation is presented by suggesting an aggregate parameter T (Section 5.1) whose numerical value represents overall impacts of technology that considers environmental, societal, economic and technological dimensions. The limitation of this paper is that it only proposes a quantitative framework to assess aggregated technological roles and impacts, however, similar qualitative conceptual framework is also needed.

This paper highlights the importance of adopting a system thinking based holistic approach that takes interactions among technological, environmental, economic and societal dimensions into consideration while setting policies for technology and the environment. Since these dimensions are intimately connected, policies informed by studies that only consider technology, economy, society or environment in isolation are unlikely to be optimal.

Holistic evaluation framework for technology proposed in this paper aids in systematic and objective assessment of roles of technology in green growth versus degrowth debate.

References

Anadon L.D., et al. (2016). Making technological innovation work for sustainable development. *Proceedings of the National Sciences of the United States of America*, 113 (35): 9682-9690. https://doi.org/10.1073/pnas.1525004113.

Anand S. and Sen A.K. (1994). Human Development Index: Methodology and Measurement. Human Development Report Office – Occasional Papers. Available at: https://ora.ox.ac.uk/objects/uuid:98d15918-dca9-4df1-8653-60df6d0289dd/download_file?file_format=application/pdf&safe_filename=HDI_methodology.pdf&type_of_work=Report.

Asayama S. and Ishii A. (2017). Selling stories of techno-optimism? The role of narratives on discursive construction of carbon capture and storage in the Japanese media. *Energy Research & Social Science*, 31: 50-59. https://doi.org/10.1016/j.erss.2017.06.010.

Bernauer T., Koubi.T.B.V. (2012). Environmental changes and violent conflict. *Environmental Research Letters*, 7 (1).

Bhargawa A., Singh A.K. (2019). Solar irradiance, climatic indicators and climate change – An empirical analysis. *Advances in Space Research*, 64 (1): 271-277. https://doi.org/10.1016/j.asr.2019.03.018.

Biggeri M. and Mauro V. (2018). Towards a more 'Sustainable' Human Development Index: Integrating the environment and freedom. *Ecological Indicators*, 91: 220-231. https://doi.org/10.1016/j.ecolind.2018.03.045.

Boonstra W.J. and Joosse S. (2013). The Social Dynamics of Degrowth. *Environmental Values*, 22 (2): 171-189.

Buch-Hansen H. (2018). The Prerequisites for a Degrowth Paradigm Shift: Insights from Critical Political Economy. *Ecological Economics*, 146: 157-163. DOI:10.1016/J.ECOLECON.2017.10.021.

Burke P.J., Csereklyei. Z. (2016). Understanding the energy-GDP elasticity: A sectoral approach. *Energy Economics*, 58: 199-210. DOI: 10.1016/j.eneco.2016.07.004.

Čavoški A. (2017). The unintended consequences of EU law and policy on air pollution. *Review of European, Comparative and International Environmental Law*, 26:255–265. https://doi.org/10.1111/reel.12211.

Chenoweth J. and Feitelson E. (2005). Neo-Malthusians and Cornucopians put to the test: *Global 2000* and *The Resourceful Earth* revisited. *Futures*, 37 (1): 51-72. https://doi.org/10.1016/j.futures.2004.03.019.

Hasan D., Yüksel S., Adalı Z. and Aydın R. (2019). Evaluating the Role of Research and Development and Technology Investments on Economic Development of E7 Countries. In: *Organizational Transformation and Managing Innovation in the Fourth Industrial Revolution*, DOI: 10.4018/978-1-5225-7074-5.ch013.

Doris F., et al. (2020). Which Way Forward in Measuring the Quality of Life? A Critical Analysis of Sustainability and Well-Being Indicator Sets. *Global Environmental Politics*, 20 (2): 12-36. https://doi.org/10.1162/glep_a_00554.

Drupp M.A., Meya J.N., Baumgärtner S., Quaas, M.F. (2018). Economic Inequality and the Value of Nature. *Ecological Economics*, 150: 340-345. https://doi.org/10.1016/j.ecolecon.2018.03.029.

Feenberg A. (1990). The Ambivalence of Technology. *Sociological Perspectives*, 33 (1): 35–50. https://doi.org/10.2307/1388976.

Gonella F. et al. (2019). Is technology optimism justified? A discussion towards a comprehensive narrative. *Journal of Cleaner Production*, 223: 456-465. https://doi.org/10.1016/j.jclepro.2019.03.126.

Grunwald A. (2018). Diverging pathways to overcoming the environmental crisis: A critique of eco-modernism from a technology assessment perspective. *Journal of Cleaner Production*, 197 (2): 1854-1862. https://doi.org/10.1016/j.jclepro.2016.07.212.

Guo L.L, Qu Y., and Tseng M.L. (2017). The interaction effects of environmental regulation and technological innovation on regional green growth performance. *Journal of Cleaner Production*, 162: 894-902. https://doi.org/10.1016/j.jclepro.2017.05.210.

Hernandez Y, Naumann G., Corral S. and Barbosa P. (2020). Water Footprint Expands with Gross Domestic Product. *Sustainability*, 12 (20): 8741. https://doi.org/10.3390/su12208741.

Jaffe A.B., Newell R.G. and Stavins R.N. (2003). Chapter 11 - Technological change and the Environment. *Handbook of Environmental Economics*, 1: 461-516. https://doi.org/10.1016/S1574-0099(03)01016-7.

Kahneman D. (1994). New Challenges to the Rationality Assumption. *Journal of Institutional and Theoretical Economics* (JITE) / Zeitschrift für die gesamte Staatswissenschaft, 150 (1): 18-36.

Keary M. (2016). The New Prometheans: Technological Optimism in Climate Change Mitigation Modelling. *Environmental Values*, 25 (1): 7-28.

Kerschne C. and Ehlers M.H. (2016). A framework of attitudes towards technology in theory and practice. *Ecological Economics*, 126: 139-151. https://doi.org/10.1016/j.ecolecon.2016.02.010.

Lawson, C. (2008). An Ontology of Technology: Artefacts, Relations and Functions. *Techné: Research in Philosophy and Technology*, 12 (1): 48-64. https://doi.org/10.5840/techne200812114.

Laugs G.A.H. and Moll H.C. (2017). A review of the bandwidth and environmental discourses of future energy scenarios: Shades of green and gray. *Renewable and Sustainable Energy Reviews*, 67: 520-530. https://doi.org/10.1016/j.rser.2016.09.053.

Leoncini, R. (1998). The nature of long-run technological change: innovation, evolution and technological systems. *Research Policy*, 27 (1): 75-93. https://doi.org/10.1016/S0048-7333(98)00025-0.

Link A. N. 1993. Evaluating the Advanced Technology Program: a preliminary assessment of economic impacts. *International Journal of Technology Management*, 8 (6-8). DOI: 10.1504/IJTM.1993.025808.

Mercure J.F., et al. (2016). Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Global Environmental Change*, 37: 102-115. https://doi.org/10.1016/j.gloenvcha.2016.02.003.

Mirza M.U., Richter A., van Nes E.H. and Marten Scheffer M. (2019). Technology driven inequality leads to poverty and resource depletion. *Ecological Economics*, 160: 215-226. https://doi.org/10.1016/j.ecolecon.2019.02.015.

Modrak V. and Soltysova Z. (2018). Process modularity of mass customized manufacturing systems: principles, measures and assessment. *Procedia CIRP*, 67: 36-40. https://doi.org/10.1016/j.procir.2017.12.172.

Munir K. and Ameer A. (2018). Effect of economic growth, trade openness, urbanization, and technology on environment of Asian emerging economies. *Management of Environmental Quality*, 29 (6). https://doi.org/10.1108/MEQ-05-2018-0087.

Nasrollahi Z., Hashemi M.S., Bameri S. and Taghvaee V.M. (2020). Environmental pollution, economic growth, population, industrialization, and technology in weak and strong sustainability: using STIRPAT model. *Environment, Development and Sustainability*, 22: 1105–1122.

OECD. (2020). OECD Work on Green Growth 2019-20. *The Organisation for Economic Co-operation and Development*. Available at: https://issuu.com/oecd.publishing/docs/gg_brochure_2019_web.

Perez C. (2016). Capitalism, Technology and a Green Global Golden Age: The Role of History in Helping to Shape the Future. *BTTR Working Paper Series*. Available at: https://beyondthetechrevolution.com/wp-content/uploads/2014/10/BTTR_WP_2016-1.pdf.

Safarzyńska K. and den Bergh J.C.J.M. (2017). Integrated crisis-energy policy: Macro-evolutionary modelling of technology, finance and energy interactions. *Technological Forecasting and Social Change*, 114: 119-137. https://doi.org/10.1016/j.techfore.2016.07.033.

Sagar A.D., and Najam A. (1998). The human development index: a critical review. *Ecological Economics*, 25 (3): 249-264. https://doi.org/10.1016/S0921-8009(97)00168-7.

Sampson R. J. (2017). Urban sustainability in an age of enduring inequalities: Advancing theory and ecometrics for the 21st-century city. *PNAS*, 114 (34): 8957-8962. https://doi.org/10.1073/pnas.1614433114.

Sandberg M., Klockars K. and Wilén K. (2019). Green growth or degrowth? Assessing the normative justifications for environmental sustainability and economic growth through critical social theory. *Journal of Cleaner Production*, 206: 133-141. https://doi.org/10.1016/j.jclepro.2018.09.175.

Vélez-Henao J.A., Vivanco D.F., and Hernández-Riveros J.A. (2019). Technological change and the rebound effect in the STIRPAT model: A critical view. *Energy Policy*, 129: 1372-1381. https://doi.org/10.1016/j.enpol.2019.03.044.

Vinuesa R., et al. (2020). The role of artificial intelligence in achieving the Sustainable Development Goals. *Nature Communications*, 11, Article number: 233.

Whyte K.P., Gunderson R. and Clark B. (2017). *Is Technology use insidious?* In: Philosophy, Technology, and the environment. Kaplan, David M. (ed). The MIT Press.

Wilson C., Grubler A., Bento N., Healey S., Stercke S.D. and Zimm C. 2020. Granular technologies to accelerate decarbonization. *Science*, 368 (6486): 36-39. DOI: 10.1126/science.aaz8060.