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"Chapter 33: Beyond systems analysis to a multidimensional approach in technology assessment by Roh Pin Lee & Witold-Roger Poganietz"

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33. Beyond systems analysis to a multidimensional approach in technology assessment

Roh Pin Lee and Witold-Roger Poganietz

INTRODUCTION

An important task of systems analysis is the description and evaluation of technologies which are embedded in a larger system, as well as the identification and qualification of associated political measures and strategies (Grunwald 2019; Coates 1982; see chap. 32). In addition to identifying (mostly techno-economic) structures and behavior patterns in systems, it furthermore determines alternative action-oriented solutions and comparatively evaluates their consequences for the system (Quade 1968). Systems analysis thus addresses a core aspect of technology assessment (TA) by generating valuable structured and system-oriented knowledge to inform socio-political discourse and support decision processes across a wide range of contexts.

The context-related application of systems analysis has led to a range of approaches. These are traditionally drawn mainly from the fields of engineering, economics, and natural sciences, with a predominant focus on empirical and quantitative methodologies to quantify relevant (technological-ecological-economical) aspects that are associated with technology innovations and deployments (Poganietz/Lee 2021). However, the empirical model-based approaches utilized for systems analysis challenge its contributions in informing and supporting socio-political discussions, decision processes, and measures development at the nexus of science, technology, policy, and society. This is because the restriction of the analysis scope to problem and action areas that can be empirically modeled and evaluated quantitatively neglects the consideration of non-tangible factors (for example, risk perception, societal acceptance) that cannot be determined quantitatively. This limits the effectiveness of developed actions and solutions, as potential areas of societal conflicts cannot be adequately identified and/or are neglected (Lee/Bereano 1981; Coates 1976).

To increase its contribution to scientific policy advice and deliberative public debates, systems analysis has therefore extended its focus in recent years from the empirical- and quantitative-focused systems analysis to include a consideration of qualitative and intangible aspects in the socio-political dimensions. Despite this scope extension, the potential applicability and contribution of an integrated approach to generate systemic and multidimensional insights that are associated with technology innovations and deployments remain lacking in the extant literature. To address this gap, this chapter presents a multidimensional approach which integrates theoretical and conceptual approaches and methodologies from multiple disciplines, ranging from process engineering to economics and social and decision sciences for TA. Specifically, it illustrates how the multidimensional socio-technological-ecological-economical-political (STEEP) approach—building on systems analysis and integrating a consideration of the human dimension—can contribute to a systemic assessment of alternative transformation routes, based on the example of the chemical industry in Germany.

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The chapter is structured as follows. First, methodological approaches in systems analysis for technological-ecological-economical evaluations are briefly reviewed. Next, developments to support an extension of systems analysis to integrate a consideration of the human (that is, the socio-political) dimension are presented. The application of the multidimensional STEEP approach for TA is then illustrated, based on the case of chemical recycling as a potential transformation route for sustainable chemical production in Germany.

METHODOLOGICAL APPROACHES IN SYSTEMS ANALYSIS

Systems theory provides the theoretical basis for systems analysis. This was founded—among others—by Bertalanffy in the 1920s. Since the 1950s, a further elaboration indicated that its task is "… the formulation and derivation of those general principles that are applicable to 'systems' in general" (Bertalanffy 1969, p. 253). This rather "mechanistic" conception of systems theory was later challenged by cybernetics, which emphasized the need for approaches which recognize the existence of feedback mechanisms between the individual and the organization (Bertalanffy 1972; see chap. 2).

Common Approaches for Systems Analysis in TA

Generally, systems analysis encompasses a broad spectrum of engineering, natural science-based, and techno-economic-based approaches. In particular, life cycle approaches—for example, life cycle assessment (LCA), material flow analysis (MFA), the input–output approach, and optimization models—are widely utilized.

LCA aims to integrate precautionary environmental protection into decisions for product development and utilization (Bauer/Poganietz 2007). With its pronounced focus on quantifying environmental impacts along the life cycle of technologies and products via diverse impact categories (for example, global warming, resource depletion, acidification, toxicity), LCA addresses a core aspect of TA.

In contrast to LCA, MFA concentrates on a comprehensive assessment of material flows and stocks in terms of societal metabolism (Brunner/Rechberger 2016). The system defined in an MFA describes the material-bounded relationships between industries, sectors, and/or technologies manifested by the investigated material—for example, carbon—in a given region and time period, as the basis for analysis (Brunner/Rechberger 2016; Uihlein et al. 2006). MFA thus supports TA by providing a comprehensive overview of material flows from resource extraction, its processing into products in individual economic sectors via respective technologies (available today, or in the future if applicable), as well as its use and utilization based on technical efficiency variables known today or expected in the future (Uihlein et al. 2006).

Rather than focusing on technologies and material flows as in the MFA, the input–output approach assesses interdependencies between sectors of an economy or several economies (Nakamura/Kondo 2009; Miller/Blair 1985). Such analyses of technical progress in individual sectors, as well as the influence of technology-related economic policy measures on sectoral value creation, jobs, and the environment, can play an important role in informing societies and decision-makers via TA (Nakamura/Kondo 2009; Miller/Blair 1985).

Finally, optimization models aim to determine the best solution for the system under investigation. Targets and objectives can differ, for example, from minimizing costs to mini-

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mizing greenhouse gas emissions of a sector and/or a national economy (Seager/Theis 2002). Especially for TA in the energy context, optimization models play an important contributing role alongside LCA.

Extending Systems Analysis to Consider the Human Dimension in Socio-Technical Systems

Technology developments and deployments take place in a socio-technical system which is made up of interrelated components ranging from physical artifacts, organizations, natural resources, informational elements, and legislative artifacts to human elements which are connected in a complex network and infrastructure (Geels 2004; Hughes 1987; Unruh 2000). The interaction and co-evolution of technologies and associated infrastructures with institutions and societal actors (Lee/Gloaguen 2015) are thus integral aspects to be considered in TA (see also chap. 8). However, such qualitative human aspects are generally not addressed in the predominantly empirical and quantitative focus which is typical for traditional systems analysis approaches. The increasing awareness and recognition of the significance and importance of socio-political factors in influencing acceptance/resistance towards the development and implementation of technological innovations have thus led to diverse approaches to determine and integrate qualitative and intangible aspects of socio-technical systems in systems analysis.

In engineering- and natural-science-based systems analysis, this is manifested in the expansion of the analysis space and system boundaries to include societal aspects. For instance, life cycle sustainability assessment (LCSA) addresses the three sustainability dimensions of environment, economy, and society via the application of life cycle approaches, namely LCA, life cycle costing (LCC), and social LCA, to assess environmental, economic, and societal impacts, respectively (Klöpffer 2014; see chap. 32). It thus represents a transdisciplinary integrative framework which extends traditional systems analysis to address potential societal impacts in sustainability evaluation (Guinée 2016). An alternative approach is the coupling of MFA with structural agent analysis. Specifically, building on an MFA, main actors of a system can be identified. Subsequently, important motives for their actions (for example, attitudes, values, income, and social integration) can be assigned and weighted according to their importance for the interaction with other actors (Binder 2007; Fuss et al. 2021).

Similar developments are also observable in economic-based systems analysis approaches. For instance, a consideration of societal parameters (for example, attitudes, values, perceptions) in economic models can support a better determination of relative costs for the development and deployment of (current and future) technologies in a socio-technical system. However, such parameters—generally used to justify variations in certain exogenous policy variables—are often not disclosed by modelers, and are assumed to be constant over time, thus neglecting potential impacts of changing socio-political framework conditions (Weimer-Jehle et al. 2020).

Despite the above developments, the qualitative and intangible nature of the human dimension in socio-technical systems continues to challenge systems analysis. To address this, the multidimensional STEEP approach builds on the strengths of systems analysis in quantifying techno-ecological-economical aspects associated with technology innovations and deployments, and complements it with insights into qualitative and intangible aspects in the human dimensions. This integrated approach—where systems analysis is supported with an identification of potential areas of societal conflicts—thus increases the effectiveness and

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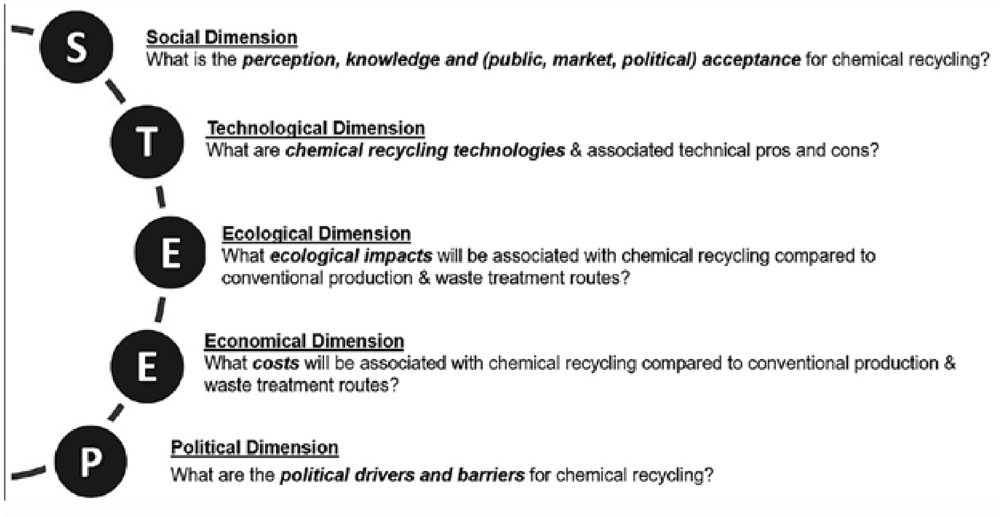
contributions of systems analysis to TA in informing and supporting socio-political discourse, decision processes, and measures development at the nexus of science, technology, policy, and society. In the following sections, the STEEP approach is illustrated by the case of chemical recycling to assess its potential contribution to the sustainability transformation of the German chemical industry.

MULTIDIMENSIONAL STEEP APPROACH FOR AN INTEGRATED TA OF CHEMICAL RECYCLING

The chemical industry traditionally relies on fossil resources (that is, oil, natural gas, coal) for its production. As a carbon-intensive industry, this sector is facing increasing pressure to transform its production processes so as to contribute to decarbonization and circularity. In this context, chemical recycling (CR)—in enabling the use of carbon-containing waste materials as alternative carbon feedstock to conventional fossil resources for chemical production—has thus been gaining increasing global attention.



Source: Lee (2022).

Figure 33.1 Research questions answered via the STEEP approach

The transformation of the chemical industry is not a one-dimensional phenomenon. Not only does it encompass technical, ecological, and economical aspects, it is also embedded in multifaceted social and political contexts. As CR consists of a range of emerging technologies that are in the process of establishing themselves on the market, there is considerable controversy about its contribution to a low carbon and circular economy. The following shares selected highlights to illustrate how the STEEP approach—in building on systems analysis and integrating social and decision sciences methodologies—can enable a systemic TA for

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rich and multifaceted insights into the multidimensional socio-technological-ecological-economical-political opportunities and challenges which are associated with CR (Lee 2022). The case of Germany illustrates how this multidimensional TA approach could contribute to informing decision-making and socio-political discourse on CR as a potential transformation route for sustainable chemical production in the country. Figure 33.1 presents an overview of research questions addressed using the STEEP approach.

Social Dimension (S̲TEEP)

Carbon resources—rather than CR technologies—form the starting point for the multidimensional TA to enable deeper insights into human-related factors which may be underpinning public, market, and political acceptance/resistance for CR developments and deployments. Drawing on path dependence, risk perception, and decision sciences literature, the following were assessed (Lee 2019):

- Do citizens know what carbon-containing resources can potentially be used as raw material for chemical production?
- What mental imageries do citizens commonly associate with the use of domestic carbon carriers for chemical production, and how are these mental imageries affectively evaluated (that is, imagery-specific affect)?

Via a representative (telephone) survey study—implemented with the support of a professional survey company in Germany in 2017—the following insights were generated.

Firstly, a large proportion of the participants were found to be wrong in their beliefs regarding what is a carbon source and constitutes a potential raw material for chemical production. This applies not only for conventional chemical feedstock (that is, crude oil and natural gas) but also for diverse potential domestic primary (that is, biomass and coal) and secondary (that is, carbon dioxide and waste) carbon alternatives. For waste, almost half of the German participants were not aware that it could potentially be used as an alternative chemical feedstock. Insights into such misconceptions are important, as they could influence public support/resistance towards proposals to develop domestic carbon-containing waste resources as feedstock alternatives for the chemical industry.

Secondly, studies in the field of risk perception using the word association technique have demonstrated a strong relationship between imagery, affect, and decision-making. This methodology has been utilized especially in the energy context to determine the underpinnings of support/resistance towards diverse energy sources and associated technologies (Lee 2015). In the chemical context, the majority of Germany participants were observed to have no dominant mental associations with oil, biomass, coal, carbon dioxide (CO_2) or waste as chemical feedstock. Since a strong association of carbon carriers with specific affective imageries could act as a “fast and frugal” heuristic to facilitate quick, easy, and efficient judgment and decision-making, this lack of mental associations strongly suggests that German citizens are missing experience of or exposure to what constitutes potential transformation options for the chemical sector.

The analyses along the social dimension thus identified a lack of public knowledge and awareness regarding the potential of waste (and other carbon resources) as domestic carbon feedstock alternatives for the German chemical sector. This points to the need to encourage public debates and discourse about this issue, so that the German public could gather enough

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information and experience to make an informed decision on whether CR is perceived as a desired transformation option for the chemical industry.

In view of the identified lack of public awareness and knowledge, a second investigation along the social dimension focused on an informed audience—rather than the general public—in order to generate qualitative and multifaceted insights relating specifically to CR perceptions. The aim was to enable in-depth and constructive input to inform socio-political discussions and support identification of regulatory and legislative needs for regulating CR implementation. The following questions were evaluated (Lee et al. 2021):

- What is understood as CR?
- What are viewed as possible input materials/feedstock and output products from CR?
- What are perceived (dis)advantages of CR compared to conventional recycling and recovery (that is, incineration) methods?
- What are perceived obstacles for CR implementation, and what steps are deemed necessary to overcome them (that is, recommendations for CR implementation)?

As CR is an emerging theme, an exploratory approach comprising of a qualitative online survey and a semi-structured workshop discussion was utilized to collect rich qualitative data to facilitate a deeper understanding of how CR is viewed, and its perceived potential to contribute to the transformation of the chemical industry. This methodology enabled the following insights:

- Similar to CR discussions in the socio-political domain, participants' understanding of CR spanned three components, namely waste as input for the production of outputs such as gases, oils, and basic chemicals, via thermochemical conversion processes which break down inputs into molecules.
- In contrast to the public and political focus on plastics, participants saw the need to expand the CR focus from *Plastics-to-Plastics* to include other waste inputs and a broader range of outputs (that is, *Waste-to-Chemicals*).
- In comparison to conventional recycling and thermal treatment methods, CR was associated with significant benefits, especially in terms of resource conservation, reduced environmental impacts, efficiency, technological advantages, as well as product and input flexibility.
- CR implementation was perceived to be challenging due to considerable obstacles along technological, institutional, and human dimensions.
- Measures perceived to be necessary to support CR implementation ranged from addressing information gap and misconceptions, promoting intersectoral cooperation, to supporting regulatory frameworks and funding for research and development (R&D) and reference projects.

These insights thus provided valuable information to inform and support efforts to determine the development and prioritization of policies and measures by policymakers to promote or regulate emerging CR technologies.

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Technological Dimension (S<u>T</u>EEP)

CR processes can generally be classified into four categories: liquefaction, gasification, depolymerization, and solvent-based purification. Drawing on expertise from the fields of process and chemical engineering, an identification of main process steps, potential process variations, as well as key process characteristics of each CR route supported a technical assessment of the suitability of differing CR processes for specific waste feedstocks (for example, pure plastic waste streams, mixed plastic waste, municipal solid waste), the potential for integration of main CR products (for example, carbon monoxide (CO); hydrogen (H_2); pyrolysis oils) into existing waste management and chemical productions routes, other site integration opportunities, as well as required treatment for by-products (Keller et al. 2022a). Such information also formed an important basis for subsequent ecological and economical evaluations to support accurate and realistic determination of associated environmental impacts and costs (Keller et al. 2022b).

Additionally, process chain simulations (for example, via ASPEN PLUS) and MFA are useful tools for the technological assessment of CR technologies. For instance, both methodologies were utilized to evaluate CO_2 emissions and carbon conversion rate (that is, carbon in chemical product/carbon in waste input) associated with the CR of waste mixtures ranging from municipal solid waste, refuse-derived-fuel (RDF), and sewage sludge, to waste wood via waste gasification (Seidl et al. 2021). Results thus provided valuable quantitative insights regarding the potential contribution of waste gasification to reducing the carbon footprint and increasing circularity in the German chemical sector.

Ecological Dimension (ST<u>E</u>EP)

LCA is a powerful method for determining ecological impacts that are associated with different technologies. To determine the ecological performance of CR compared to conventional waste treatment, three routes were quantitatively assessed in terms of their global warming potential (GWP), namely (Voss et al. 2021):

- Direct incineration of residual municipal solid waste (rMSW).
- Indirect incineration of RDF, generated after mechanical-biological treatment of rMSW.
- Gasification-based CR of RDF from rMSW.

The focus on rMSW—in response to findings along the social dimension (see above) which pointed to the need to expand CR focus from the predominant *Plastics-to-Plastics* to include other waste inputs and a broader range of outputs—enabled an evaluation of whether CR in the form of waste gasification could contribute to a circular carbon economy via recirculating heterogenous and "dirty" carbon-containing waste materials back into the production cycle as alternative chemical feedstock. This not only avoids a competition with mechanical recycling for pure (plastic) waste streams—a key reason for the controversy revolving around CR's role in the waste hierarchy—it furthermore addresses gaps in waste management, circular economy, and transition literature, in addition to providing valuable input to support socio-political discussions regarding the climate potential of CR for mixed or residual waste which is not recyclable via conventional recycling techniques.

Process chain simulation and MFA (tools utilized for assessments along the technological dimension) provided a grounded basis for the comparative LCA. Results indicated that while

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all three routes are associated with negative GWP (that is, positive global warming reduction potential), that of incineration-based routes—both direct and indirect—will be strongly dependent on the reference energy system. Specifically, an increased proportion of renewables in the energy system will significantly reduce the global warming reduction potential of incineration-based pathways. In contrast, CR in the form of waste gasification will continue to exhibit—albeit reducing—climate impacts.

Economical Dimension (STEEP)

LCA evaluation along the ecological dimension pointed to the positive global warming reduction potential of CR in the form of waste gasification. However, this positive climate effect comes at a price. To determine the economic viability of waste gasification, two aspects were evaluated, namely fixed capital investment (FCI) as well as profitability in terms of net present value (NPV), dynamic payback period (DPP) and levelized cost of carbon abatement (LCCA). Results, building on the basis provided by process chain simulations and MFA (Voss et al. 2021), indicated that:

- CR in the form of waste gasification will require higher FCI compared to direct and indirect incineration.
- Upscaling will improve CR economic performance (in terms of NPV, DPP, and LCCA).
- Sensitivity analyses showed that indirect economic incentives by penalizing CO_2 emissions from waste incineration, and direct economic incentives via price premiums for CR products, would increase CR profitability such that it is comparable to (or even more attractive than) incineration-based routes.

Political Dimension (STEEP)

To enable additional insights into socio-political factors influencing CR developments and deployments, opportunities and challenges as well as drivers and obstacles along the political dimension were investigated. To support an appraisal of the politics of a transition in the chemical industry, the following three political indicators were evaluated (Lee/Scheibe 2020): supply security, carbon pricing, and regulatory framework.

The analysis—carried out in 2020—focused on crude oil and natural gas as conventional chemical feedstock, as well as biomass (that is, biogas and wood waste), coal (bituminous coal and lignite), waste (municipal waste, sewage sludge, and plastics), and CO_2 as alternative domestic primary and secondary carbon raw materials for the German chemical industry

Supply security was operationalized via two quantitative sub-indicators, namely *Reserves-to-Production-Ratio* (RPR) and *import dependency.* Results indicated that natural gas has the highest import dependency scores (especially in Russia) and consequently the highest risk of a potential supply disruption (which Germany and Europe experienced painfully in 2022 as a result of the Russia–Ukraine war). In contrast, despite a higher overall import share, crude oil faces lower risk as imports are more diversified. Further qualitative considerations such as interdependence, European Union (EU) market attraction, and power relations, were also analyzed to enable a richer and more encompassing picture of supply security to inform strategic policy development and investment decisions.

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With regard to carbon pricing—a central mechanism used in the EU to reduce carbon emissions through incentivizing investments in more efficient technologies, cleaner fuels, and green energy—it is projected that carbon prices will raise considerably in the EU in the coming decades to facilitate the achievement of the EU's decarbonization goals. This is anticipated to change the merit order in electricity generation: that is, utilities will be motivated to switch from coal-fired power generation to alternatives, which will in turn have considerable impacts on the availability of diverse carbon feedstock alternatives for the German chemical industry.

Furthermore, the utilization of diverse carbon resources as feedstock alternatives by the chemical industry is also determined to a large extent by European and German regulatory frameworks. A qualitative analysis of regulatory developments at both European and national levels thus provided additional insights into associated drivers and obstacles for the use of domestic carbon sources (including waste) as alternative feedstock for the German chemical industry.

CONCLUSION

Systems analysis—with its predominant focus on empirical and quantitative methodologies to quantify technological-ecological-economical aspects that are associated with technology innovations/deployments—addresses a core aspect of TA (see also chap. 32). In recent years, growing awareness and recognition that technology developments and deployments are taking place in a socio-technical system have highlighted the significance and importance of integrating qualitative and intangible aspects of the human (that is, socio-political) dimension in evaluations. This chapter provides a brief overview of common approaches for systems analysis, as well as recent developments in extending systems analysis methodologies to integrate a consideration of the human dimension in socio-technical systems. Additionally, a multidimensional STEEP approach to extend systems analysis towards a systemic approach for TA is introduced.

The STEEP approach is illustrated by the case of CR as a potential transformation route towards sustainable chemistry in Germany. Research findings along multiple dimensions showed that CR, in using carbon-containing waste as chemical feedstock, could contribute to the substitution of imported fossil raw materials for chemical production in Germany. This in turn would lead to an increase in raw material supply security. Moreover, CR is perceived to have applicability beyond *Plastics-to-Plastics*. In facilitating the recycling of challenging waste such as unsorted, mixed, and contaminated municipal solid waste to enable *Waste-to-Products*, CR could provide an environmentally friendly alternative to incineration and reduce Germany's carbon footprint. However, to date, public awareness and knowledge of CR are very limited. These, together with the observed widespread misconceptions, could hinder the development and deployment of CR projects. Furthermore, under current regulatory frameworks, CR would be associated with significant investment costs, and also faces competitive disadvantages compared to mature and established industries such as petrochemistry and waste incineration. Highlights of research insights gained along the STEEP dimensions shared in this chapter thus illustrate how an application of this multidimensional approach could contribute to a rich and multifaceted TA to inform socio-political discourse and support decision processes.

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