N. Thonemann, A. Schulte, and D. Maga. Life Cycle Assessments for Emerging Technologies: A Systematic Review and Methodological Guidance

Summary

This supporting information provides a table with detailed information on the reviewed case studies that conduct prospective LCAs on emerging technologies.

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Table S1: Reviewed prospective LCA case studies on emerging technologies

	Challenges										Interpretation	
	Comparability				Data					Uncertainty		
	Aim	Defining the functional unit	System boundaries	LCIA categories[1]	Foreground data availability	Background data availability	Quality	Foreground system scaling	Background system scaling		Interpretation methodology (scale-up)	Results (Lab-scale vs. scale-up)
Arvidsson et al. [1]	Environmental comparison of production routes of chemicals	Noticed the issue (output-based)	Not noticed an issue (cradle to gate)	HT, WU, ET	Patents	Considers the foreground system solely	Not mentioned	Scenario ranges	Considers the foreground system solely	Parameter variation	Possible to conduct upscaling and prospective LCA	Not possible to draw any generally valid conclusion
Arvidsson & Molander. [2]	Assessing environmental impacts of nanomaterials and comparison with previous LCA studies	Noted that more specific functional units may be needed for specific applications (output-based)	Not noticed an issue (cradle to gate)	CC, AC, WU	Experiments	ecoinvent	Not mentioned	Predictive scenarios (experts, scenarios from literature)	ecoinvent	Parameter variation	In the future role of time scale and manufacturing readiness level (MRL) needs to be considered	Pursue new production routes
Arvidsson et al. [3]	Environmental Comparison of chemical production scales and comparison of lab, pilot, and an industrial-scale	Noticed the issue (output-based)	Existence of many downstream applications mentioned. However, exclusion of those (cradle to gate)	CC, ET, AC	Lab-scale data	ecoinvent	Not mentioned	Scenario ranges (worst- and best-case, assumptions)	Different background data (worst- and best-case), ecoinvent	Consider uncertainty analysis strategies	Background system has an influence, foreground and background change with time: Temporal Robustness	Lower environmental impacts for the scale-up system

[1] Midpoint methods: Climate change, CC; Ozone depletion, OD; Human toxicity, HT; Particulate matter formation, PMF; Photochemical ozone formation, POF; Ecotoxicity, ET; Acidification, AC; Eutrophication, EU; Land use, LU; Water use, WU; Abiotic resource use, ARU; Ionizing radiation, IR. Endpoint methods: Human health, HH; Natural environment, NE; Natural resources, NR

Baresel et al. [4]	Environmental comparison of different plant sizes of wastewater treatment	One functional unit defined, but consider different reuse categories (output-based)	Not noticed an issue (cradle to gate)	AC, CC, HT, ARU, POF, WU, EU	Pilot plant data	ecoinvent	Mentioned in terms of geographical representativeness	Scenario ranges (Calculations, full-scale references)	ecoinvent	Not considered	Needs to consider plant sizes and treatment technologies	Most environmental impacts are reduced as the plant size increases
Bartolozzi et al. [5]	Prospective LCA of nanostructured materials	Not noticed an issue (output-based)	Extension necessary (cradle to gate)	CC, OD, HT, PMF, IR, POF, AC, EU, ET, LU, WU, ARU	Lab-scale data	ecoinvent	Not mentioned	Predictive scenarios (Calculations, equations based on Piccinno et al. [6])	ecoinvent	Not considered	Useful for identifying highly contributing life cycle stages	Environmental impacts decrease when upscaling the emerging technology
Caduff et al. [7]	Size scaling effects of power generation	Not noticed an issue (output-based)	Not noticed an issue (cradle to grave)	CC, ET, LU, ARU	Literature	ecoinvent	Not mentioned	Predictive scenarios (Power laws, learning curves, progress rates)	ecoinvent	Not considered (Parameter variation with sensitivity analysis)	Transparency in LCA reports needs to be included	Bigger turbines have less environmental impacts
Corona et al. [8]	Environmental evaluation of different configurations of biofuel production	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, LU, ET, EU, WU	Pilot plant data	ecoinvent	Not mentioned	Predictive scenarios (simulation, assumptions, literature)	ecoinvent	Not considered (Parameter variation with sensitivity analysis)	Process flowsheet simulation and LCA as a first step	Product yield maximization showed to be the essential environmental parameter
Corona et al. [9]	Environmental comparison of process media (crops for green biorefinery conversion) for biofuel production	Not noticed an issue (input-based)	Not noticed an issue (cradle to gate)	CC, LU, ET, EU, WU	Pilot plant data	ecoinvent	Not mentioned	Predictive scenarios (simulation)	ecoinvent	Not considered	Reasonable representativeness of the relevant processes	One crop has the best performance

Fang et al. [10]	Identification of improvements for process development in wastewater treatment	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	HT	Existing processes	ecoinvent	Not mentioned	Predictive scenarios (Modeling data)	ecoinvent	Uncertainty and sensitivity assessment with the approach proposed by Claverul et al. [11]	Benefits for decision making and implementation	Some parameters have impacts on many categories whereas others only to certain categories
Garcia-Herrero et al. [12]	Environmental comparison with conventional processes for chemical production and identification of improvements for process development	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, ET, HT, POF, ARU, WU, OD, EU	Lab-scale data	ecoinvent	Not mentioned	Predictive scenarios (assumptions, simulation, literature)	ecoinvent	Not considered	Eliminate the environmental hot spots systematically	The new process is not sustainable
Gargalo et al. [13]	Identification of improvements for process development in chemical production and reporting and interpreting uncertainty	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, HT, ET, PMF, POF, AC, EU	Literature, experiments, pilot plant data, simulation results, stream tables	ecoinvent, literature	Not mentioned	Scenario ranges (worst- and best-case, Multidimensional matrix, Superstructure)	ecoinvent, literature	Process validation algorithm (aimed at consistent stoichiometry); Monte Carlo simulation	Combining risk management and LCA to extend the usual practice	The new process has the most significant potential to reduce environmental impacts
Gavankar et al. [14]	Size scaling effects in nanomaterial production	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, EU, AC, ET, WU, POF	Lab-scale data	ecoinvent	Pedigree matrix approach	Predictive scenarios (based on technology readiness level (TRL) and MRL)	ecoinvent	Uncertainty quantification via pedigree matrix	Provide an initial baseline and nonlinear effects of scaling up	Reduction of impacts through upscaling

Gear et al. [15]	Environmental comparison of design changes in waste treatment and identification of improvements for process development as well as of key impact categories	Not noticed an issue (output-based)	Not noticed an issue (cradle to grave)	CC, AC, ET, EU, OD, WU	Pilot plant data	ecoinvent	Authors present a simple LCA toolkit which is applicable without requiring high-quality data	Predictive scenarios (initial base case, Design modifications)	ecoinvent	Not considered	Normalization and ternary diagram with key impact categories to supports the technology development	The new process is a better environmental option
Gerber et al. [16]	Provision of full-scale biofuel production inventory data	Not noticed an issue (input-based)	Not noticed an issue (cradle to gate)	HH, NE, NR	Pilot plant data, literature	ecoinvent	Not mentioned	Predictive scenarios (calculations, power laws)	ecoinvent	Monte Carlo simulation	Power laws are used and confirmed useful for scaling	Not possible to draw any generally valid conclusion
Hospido et al. [17]	Review methodological issues for LCAs on emerging technologies, drawing suggestions, and application to case studies within the food-processing sector.	Physical units are preferred. Economic dimension included in the FU when required (output-based)	Steps that are not affected by the novel process are excluded (cradle to grave)	Not mentioned	Literature, lab-scale data	Literature, ecoinvent	Not mentioned	Predictive scenarios (full-scale references, modeling data)	Literature, ecoinvent	Parameter variation with sensitivity analysis	The applied method is confirmed to be useful for prospective LCAs on emerging technologies	Not possible to draw any generally valid conclusion
Janssen et al. [18]	Environmental evaluation of different configurations of biofuel production and comparison with previous LCA studies as well as the industrial-scale	Noted that more specific functional units may be needed for specific applications (output-based)	Noticed the issue. Due to lacking data, they used a cradle to gate system boundary to avoid uncertainty	CC, EU, AC, POF	Lab-scale data	ecoinvent	Not mentioned	Scenario ranges (Spreadsheet model, assumptions, modeling data)	ecoinvent	Sensitivity analysis	Further research is needed for applying prospective LCA on emerging technologies	The process with a lower yield influences impacts

Joyce et al. [19]	Anticipatory assessment of the environmental impacts of paving blocks	Not noticed an issue (output-based)	Not noticed an issue (cradle to grave)	CC, AC, PMF, POF, OD, HT, IR, EU, ET, ARU	Lab-scale data, experiments	ecoinvent	Data quality improves while process design knowledge increases	Predictive scenarios (assumptions)	ecoinvent	Sensitivity analysis for the distance parameter is done	Useful for identifying highly contributing processes	Lower environmental impacts at potential industrial scale
Kazemi et al. [20]	Assess the environmental impacts of nanomaterials	Not noticed an issue (output-based)	Not noticed an issue (cradle to use)	ET, CC, HT, WU	Experiments	ecoinvent	Not mentioned	Scenario ranges (sensitivity analysis, modeling data)	ecoinvent	Claim to calculate uncertainty using parameter variation with sensitivity analysis	Useful in an early stage of development	Increased adsorption capacity leads to higher impacts, but upscaled option performs better
Liptow et al. [21]	Environmental comparison of new production routes for biofuel production and comparison with the conventional process	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, POF, EU, AC	Pilot plant data	Literature	Not mentioned	Predictive scenarios (simulation)	Literature	Not considered	The applied method needs to be improved further	The new gasification route has higher impacts, and industrial-scale fails because of limited biomass supply
Lu et al. [22]	Ex ante LCA to assess GHG emissions and guide future developments of the novel Cl recovery process for PVC	Not noticed an issue (input-based)	Not noticed an issue (cradle to gate)	CC, ARU	Lab-scale data, Literature	Inventory Database for Environmental Analysis (IDEA)	Not mentioned	Scenario ranges (calculations, equations)	IDEA	Not considered	Approach useful to suggest development targets	Reduction of GHG emissions and energy consumption for the potential industrial-scale technology

Marco et al. [23]	Environmental impact assessment of chemicals	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	HT, POF, AC, LU, CC, OD, EU, PMF, ET, ARU	Lab-scale data, pilot plant data	ecoinvent	Not mentioned	Predictive scenarios (simulation, assumptions)	ecoinvent	Not considered	Applied method needs to be improved further	Reduction of the impacts after scaling-up from lab to pilot-scale
Muñoz et al. [24]	Prospective LCA of an off-grid solar-assisted heat pump and comparison to a reference	Not noticed an issue (input-based)	Not noticed an issue (cradle to grave)	CC, HT, PMF, IR, OD, ET, LU, AC, EU, POF, ARU	Pilot plant data, literature, assumptions	ecoinvent (consequential)	Not mentioned	Predictive scenarios (assumptions)	ecoinvent (consequential) and assumptions for the electricity mix in the period from 2012-2020	Scenario and sensitivity analysis	Prospective LCA is useful, but the preliminary results need to be validated with a real-life application	Emerging technology performs better on an industrial scale and the reference
Pallas et al. [25]	Prospective LCA to identify environmental hotspots along the development of an emerging technology without a comparison to a reference	Noticed an issue regarding the consistency of data source (output-based)	Noticed an issue regarding the inclusive of the EoL stage (cradle to gate)	CC, AC, EU, POF, ET, OD, HT, LU	Experiments, literature	ecoinvent	Not mentioned	Predictive scenarios (assumptions)	ecoinvent	Scenario analysis	The approach is useful to guide the development of emerging technologies	Comparing different emerging technologies and give guidance for upscaling
Piccinno et al. [26]	Environmental impact assessment of nanomaterials at commercial-scale	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	HT, PMF, OD, ET, AC, LU, EU, POF, CC, ARU, HH, NR, NE	Lab-scale data, literature	ecoinvent	Not mentioned	Predictive scenarios (Calculations, equations)	ecoinvent	Qualitatively stated	The framework used to compare to a linear scaling factor considered to be useful	Lower impacts for the scale-up

Pini et al. [27]	Identification of improvements/hotspots for process development in nanomaterials	Not noticed an issue (output-based)	Not noticed an issue (cradle to grave)	HT, PMF, OD, ET, AC, LU, EU, CC, ARU	No foreground system for lab-scale	ecoinvent	Not mentioned	Predictive scenarios (experiments, linear scaling rate)	ecoinvent	Parameter variation with sensitivity analysis	Future work for a complex up-scaling scheme is needed	Production stage has the highest environmental impacts
Roes & Patel [28]	Environmental comparison of new production routes with the conventional process	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC	Chemical equations	ecoinvent	Not mentioned	Predictive scenarios (modeling data, literature)	ecoinvent	Data uncertainty is discussed in the interpretation	The applied method needs to be improved further	New catalyst offers advantages but has higher impacts
Sampaio et al. [29]	Environmental impact assessment of food products	Not noticed an issue (output-based)	Noticed the issue (cradle to gate)	CC, AC, ARU, POF, OD, PMF, EU, WU	Lab-scale data	ecoinvent	Pedigree matrix approach	Predictive scenarios (literature, expert estimations)	ecoinvent	Monte Carlo simulation using values from the pedigree matrix in ecoinvent	Search for alternatives and equipment requirements	Impacts mainly result from the energy demand
Sfez et al. [30]	Identification of improvements for process development in wastewater treatment	Not noticed an issue (input and output-based)	Not noticed an issue (cradle to gate)	CC, EU, ARU	Literature, on-site visits	ecoinvent	Not mentioned	Predictive scenarios (expert estimations)	ecoinvent	Not considered	The applied method needs to be improved further especially uncertainties should be reduced	Up-scaling enhances environmental sustainability
Simon et al. [31]	Environmental impact comparison of an emerging technology and a mature technology for battery production	Introduce the analysis of the function (output-based)	Not noticed an issue (cradle to gate)	CC, AC, EU, ET, POF, ARU	Lab-scale data, experiments, literature	ecoinvent	Not mentioned	Predictive scenarios (assumptions, literature, calculations	ecoinvent	Sensitivity analysis	Application of the proposed method is meaningful but needs to be validated	Up-scaled emerging technology shows lower environmental impacts

Taelman et al. [32]	Overcome limitations of lab-scale LCA in the field of algae	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, ARU	Pilot plant data, literature	ecoinvent	Not mentioned	Scenario ranges (sensitivity analysis)	ecoinvent	Not considered	Promising results for an upscaled system	Identifies the best scenario
Tan et al. [33]	Environmental impact assessment of chemicals	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	LU	Experiments	ecoinvent	Not mentioned	Predictive scenarios (simulation)	ecoinvent	Not considered	Close to actual impacts	Upscaling performs better
Thonemann & Schulte [34]	Development of a methodology for the prospective LCA and applying it to the electrochemical reduction reaction	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, AC, ET, EU, IR, HAT, OD, POF, PMF, LU, ARU	Lab-scale data	ecoinvent (consequential)	Pedigree matrix approach	Predictive scenarios (simulation)	ecoinvent (consequential)	Monte Carlo simulation, scenario analysis, and sensitivity analysis	Promising results for an upscaled system	Identifies the best potential reactor design
Troy et al. [35]	Environmental impact assessment of energy technologies	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, HT, EU, AC, POF, ARU, ET, OD, HH	Lab-scale data	ecoinvent	Not mentioned	Scenario ranges (extreme scenarios (minimum))	ecoinvent	Not considered	Results not comparable but Indicate a direction	Decrease in all impact categories for scale-up
Tsoy et al. [36]	Guidance for the R&D of a novel coating technology regarding environmental impacts	Two functional units defined (output-based)	Not noticed an issue (cradle to grave)	CC, AC, OD, EU, ET, HT, POF, LU	Literature, company data	ecoinvent	Not mentioned	Predictive scenarios (assumptions)	ecoinvent	Sensitivity analysis	The new coatings are environmentally competitive with conventional coatings	The use of anticipatory LCA is recommended in the early stage of design
Valsasina et al. [37]	Environmental comparison with the conventional process for food production	Not noticed an issue (output-based)	Not noticed an issue (cradle to grave)	CC, OD, HT, PMF, POF, ET, AC, EU, LU, WU, ARU, IR	Experiments	ecoinvent	Not mentioned	Scenario ranges (sensitivity analysis, power laws)	ecoinvent	Sensitivity analysis	Further research is recommended	Upscaling performs better

Villares et al. [38]	Ex-ante environmental impact assessment of waste treatment	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, OD, HT, POF, ET, AC, EU, ARU	Experiments	ecoinvent	Stating that data quality is lower when applying ex-ante LCA	Scenario ranges (explorative)	ecoinvent	Not considered	Enables hotspot analysis	Upscaling performs better
Walser et al. [39]	Environmental comparison with the conventional process in the field of clothing	Noticed the issue (output-based)	Not noticed an issue (cradle to grave)	CC, ET	Literature	ecoinvent	Pedigree matrix approach	Predictive scenarios	ecoinvent	Monte Carlo-simulation	Support of policy decisions	Impacts are lower in the nanomaterials scenarios
Wender et al. [40]	Framework for anticipatory LCA in the field of energy technologies	Noticed the issue (output-based)	Noticed the issue (cradle to gate)	CC, OD, HT, PMF, POF, ET, AC, EU, LU, WU, ARU, IR	Literature	ecoinvent	Stating that data quality issue exists and cannot be overcome not even if the effort is increased	Predictive scenarios (risk research)	ecoinvent	Parameter and scenario uncertainty (pedigree matrix)	The framework is applicable to assess emerging technologies environmentally	New panels have an 80 % likelihood to have the lowest overall environmental burden
Weyand et al. [41]	A meta-LCA approach is used to assess the current and future environmental impacts of photovoltaic systems	Defined two different functional units. One for the status quo and one for the future system (output-based)	Noticed the issue (cradle to gate and cradle to grave)	CC, ET, HT, ARU	Literature	Not specified	Not mentioned	Predictive scenarios (assumptions, power laws, calculations)	Not specified	Scenario and sensitivity analysis	Harmonization approach useful to assess technologies at an early-stage while decreasing uncertainty	Organic PV technologies are the most mature and environmental competitive technology
Yao et al. [42]	Ex-ante LCA of geo-polymers produced via 3D printing	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC, EU, AC, ARU, POF, ET, OD, HAT	Literature	ecoinvent	Not mentioned	Predictive scenarios (assumptions)	ecoinvent	Scenario analysis	Implementation of ex-ante LCA is useful to support technology innovation	Environmental impacts decrease when scaling the emerging technology

Yao & Masanet [43]	Generate flexible inventory data (for emerging technologies) of chemical production	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC	Experiments	Literature	Not mentioned	Predictive scenarios (design logic approach)	Literature	Monte Carlo simulation or scenario analysis and sensitivity analysis	The used framework is flexible applicable	New ethane oxidative dehydrogenation technology has the potential to reduce impacts
Zackrisson et al. [44]	Prospective LCA of a structural battery in an electric car roof	Defined two different functional units. One for the status quo and one for the future system (output-based)	Not noticed an issue (cradle to grave)	CC, POF, ARU	Literature	ecoinvent	Not mentioned	Predictive scenarios (assumptions)	ecoinvent	Sensitivity analysis	The structural battery at a more developed stage was assessed to have less environmental impacts than the early-stage battery	Integration of chemical risk assessment in prospective LCA is useful to assess toxicological impacts
Zhou et al. [45]	Coupling of pilot plant operation and life cycle assessment within chemical production	Not noticed an issue (output-based)	Not noticed an issue (cradle to gate)	CC	Pilot plant data	ecoinvent	Data quality criteria described	Scenario ranges	ecoinvent	Propose Monte Carlo simulation	The framework is useful for environmentally assessing emerging technologies, but further research is recommended	Impacts on pilot and industrial-scale are close to each other
Zimmermann et al. [46]	Approach for prospective LCA in mobility	Not noticed an issue (output-based)	Not noticed an issue (cradle to grave)	CC, OD, HT, ET, AC, EU, LU, ARU, IR	Literature	ecoinvent	Pedigree matrix approach	Predictive scenarios	ecoinvent	Not considered	The method enables early design changes to reduce impacts	Generation and consumption of energy are the most crucial parameters

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