

Industry eco-innovation strategies for process upgrading: systemic limits of internalising externalities

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ABSTRACT

Industry has been upgrading its production processes through eco-innovation combining environmental and economic benefits, thus reducing some resource burdens which otherwise lie outside economic accounting. Some companies have shown interest in evaluating investment options for resource burdens and total value added across a whole-system value chain. Our EC research project developed a method for whole-system assessment of eco-innovation with multi-stakeholder cooperation. In three cases presented here, tensions arise among various aims, resource burdens, system levels, beneficiaries and timescales, thus complicating the concept of eco-innovation as a win-win strategy. Radical eco-innovation would depend on extra functions, value-chain actors and resource usages which can provide greater overall benefits. But such investment faces many systemic obstacles. Eco-innovation remains path dependent, thus limiting the scope to internalise environmental externalities. The tensions and difficulties cast doubt on an EC strategy emphasising uptake of eco-innovative technologies as the means to decouple economic growth from resource burdens.

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1. Introduction

For many years, industry has sought to enhance sustainability through strategies such as lean manufacturing, waste minimisation or reuse, more efficient material or energy yields and substitution of renewable energy. Such changes have been conceptualised as eco-innovation, combining ecological and economic benefits as a win-win strategy; this internalises some environmental externalities, especially through lower pollution. Benefits vary according to the choice of system boundary, as well as the choice of eco-innovation, so some companies have been taking a broader perspective.

From such a perspective, this paper discusses the following questions:

- (1) What tensions arise among various aims and benefits of eco-innovation?
- (2) What is the scope to internalise externalities, within what limits?
- (3) What are implications for EU policy frameworks?

After surveying literature on eco-innovation and value chains (VCs), this paper links those concepts through an EC-funded research project which had multi-stakeholder involvement in assessing improvement options. Each case study analyses the company context and one eco-innovation option, as a basis to address the above questions, which are answered in the Conclusion section.

2. Analytical perspectives: path-dependent eco-innovation?

This section surveys perspectives on eco-innovation and value-chain analysis, as a basis for linking them at the level of a production process, as explained in the subsequent section on Research Methods.

The term eco-innovation gives 'eco' a double meaning. This encompasses various innovations offering greater economic value and lower resource burdens; the latter category encompasses resource inputs and pollutants, which degrade resource availability. As a high-profile definition:

Eco-innovation is the introduction of any new or significantly improved product (good or service), process, organisational change or marketing solution that reduces the use of natural resources (including materials, energy, water and land) and decreases the release of harmful substances across the whole life-cycle. (EIO 2011a, 2)

Eco-innovation has been defined more broadly as 'a change in economic activities that improves both the economic performance and the environmental performance of society' (Huppes et al. 2008, 29). In the 1990s, many discussions emphasised dematerialisation, that is, reducing material inputs and thus gaining 'more for less'.

Important distinctions are warranted. Eco-innovation has various forms, for example, incremental change, or radical change in a production system. Associated with eco-efficiency improvements, 'Incremental changes refer to gradual and continuous competence-enhancing modifications that preserve existing production systems and sustain the existing networks, creating added value'. By contrast, radical innovation offers greater societal benefit but may conflict with previous investment: they 'are competence-destroying, discontinuous changes that seek the replacement of existing components' (Carrillo-Hermosilla, del Río, and Könnölä 2010, 1075).

Radical innovation overlaps with industrial symbiosis. This is an interconnected industrial system where new products evolve out of, or consume, available waste streams, and where processes are in turn developed to produce usable 'waste' (De Simone and Popoff 2000, 52–53). There have been efforts to identify existing symbioses, leading to more sustainable industrial development (Chertow 2007).

Incremental change is often conceptualised as a process upgrading which also potentially generates new functions and resource usages. In particular:

A firm can transform its internal processes by redesigning them on the basis of new environmental standards or goals. The strategy defined as 'beyond compliance leadership' can also refer to the process-upgrading framework, but it may also induce the firm to develop new functions and play a new role in its VC [value chain], therefore pointing to a functional upgrading. In the first case, this process will result in improved efficiency; in the second in a competitive advantage based on differentiation, that is, a better corporate image. (De Marchi, Di Maria, and Micelli 2013, 66)

Beyond a better overall image, companies have linked eco-innovation with specific products offering consumer benefits, which could increase the company's income through greater sales or price. Such an advantage depends on aligning product characteristics with green consumer behaviour (Jansson 2011). According to a survey of German companies, process innovations corresponded to lower profit margins than did product innovations (Rennings and Rammer 2011). Thus, innovation for process upgrading may have weaker incentives than for 'green products', whose sales expand material consumption and thus resource usage. Indeed 'ecoefficiency must fit within the growth-paradigm and, in fact, it is subtly designed to re-enforce it' (Welford 1998, 4).

Eco-innovation has been widely seen as 'enabling win-win synergies' (OECD 2012), but such options may be rare, so tensions arise among various objectives. 'Like any innovator, an eco-innovator must deal with trade-offs. The trade-offs depend on the state of technology and contextual factors such as prices and infrastructure' (Kemp and Oltra 2011, 250). Trade-offs encompass diverse environmental harms that could be internalised, alongside the economic aims which generally have driven eco-innovation. 'While end-of-pipe technologies only had one environmental goal to fulfill in the past, and incurred some extra costs, the new generation of integrated environmental technologies

– known as cleaner production – is a complex innovation activity with more than one aim’ (Horbach, Rammer, and Rennings 2012, 113).

As a related obstacle to eco-innovation, decision-making responsibilities are often fragmented—between economic and environmental criteria, between energy and water supplies, and between value-chain stages, especially across companies. Such fragmentation misses opportunities for eco-innovation. ‘Establishing framework conditions which foster innovation and transparency and which allow sharing responsibility among stakeholders will amplify eco-efficiency for the entire economy and deliver progress toward sustainability’ (WBCSD 2000, 6–7).

Environmental sustainability improvements were once seen mainly as costs. According to a survey of numerous Europe-based large companies, many have integrated sustainability into their innovation strategies: ‘integration is achieved through formal consideration of sustainability topics with regard to innovation in pre-development or stage-gate processes and related guidelines’. They have developed greater capacity for such integration, especially in response to more stringent regulation of resource burdens. Such responses depend on company knowledge-bases which ‘are path dependent and often determined by irreversible historic processes’ (Wagner and Llerena 2011, 756, 759).

As a general obstacle, industrial interests seek ‘improvement options that only fit into the existing system and which, as a result, stimulate a “lock-in” situation’ (Kemp and Rotmans 2005, 49). Lock-in can result from path dependence, whereby previous trajectories constrain later ones (Garud, Kumaraswamy, and Karnøe 2010, 768). Path dependence generally favours incremental rather than radical change.

Eco-efficient innovation can internalise some negative externalities, that is, environmental burdens which otherwise lie outside economic accounting. But such innovation has limited capacity to address common-good environmental problems, especially where significant externalities are inherent to a production chain:

... business institutions are able to conquer win-win markets, thereby internalising negative externalities, if they are guided by normative decision rules and by a flexible regulatory framework that sets incentives for knowledge creation ... Business institutions can do a good job in internalising externalities, but they surely cannot completely solve common-good problems ... Governments are responsible for setting the framework conditions and organising a process by which new knowledge on managing the commons can be gained, while markets are responsible for finding and managing solutions ... (Bleischwitz 2003, 454, 462)

Beyond eco-efficient innovation, comprehensive solutions depend on ‘new system designs which completely restructure existing production chains’ (Bleischwitz 2003, 453), also known as radical innovation.

For a radical sustainability transition, environmental innovations generally save input factors (energy and/or materials) rather than improve quality in ways which could increase consumer price or sales. Towards reducing greenhouse gas (GHG) emissions, for example, eco-innovation may depend on environmental regulation forcibly internalising costs of environmental harm by adopting available technologies (van den Bergh, Truffer, and Kallis 2011, 4). Indeed, the EU’s relatively more stringent regulation has stimulated some eco-innovation, especially in water-use systems.

But regulatory pressures can have contradictory effects on whether or how companies adopt water eco-innovation. Specific regulatory criteria may favour currently available technologies and so hinder more resource-efficient ones. Regulations ‘do not support radical innovation and may unintentionally support the existing technological regime’ (EIO 2011b, 53).

This path dependence is reinforced by narrow evaluations. Eco-innovation improvements have been generally evaluated at a specific site within a company or at most within its overall internal processes (e.g. Van Caneghem et al. 2010). Even when a company carries out a life-cycle analysis of wider environmental effects, the economic analysis generally focuses on the company only. A wider scope for both parameters is necessary to evaluate alternative options for supply chains (Michelsen, Fet, and Dahlsrud 2006).

Eco-efficiency analyses often neglect wider economic aspects, especially changes in VCs: ‘the point is to understand how firms may reduce the impact of all the activities performed to realise their products, including those of suppliers and sub-suppliers, therefore moving the focus from firm-level strategies to VC-level strategies’ (De Marchi, Di Maria, and Micelli 2013, 64).

Such a perspective can consider broader externalities to be internalised.

3. EcoWater project: research methods and focus

Our EU-funded research project, EcoWater, developed a methodology and framework for assessing eco-efficiency on the meso-level, also known as the whole system. This is defined as interactions and interdependencies among heterogeneous actors in a production process (Schenk, Moll, and Uiterkamp 2007). This level encompasses all inputs, valuable products, waste, its treatment, etc. According to one study, ‘the meso level is the most challenging from the point of view of gathering evidence, as it requires information from many agents’ (Reid and Miedzinski 2008, 22).

In the project, assessments followed resource burdens and total value added (TVA) across a product’s VC, for example, among water suppliers, water users and wastewater treatment (WWT) providers. The project compared options for innovative practices within a specific water-service system; this includes the entire range of water services required to render water suitable for a specific water-use purpose, and safely discharging it to the water environment.

By operationalising those concepts, the EcoWater project aimed: to assess the meso-level eco-efficiency of various options for innovative practices (including technologies), to compare their relative benefits, to analyse factors influencing decisions to adopt such practices, to inform better decision-making and to inform policy frameworks which could promote such decisions. The project attracted cooperation from companies which already had invested in process eco-innovation; they seek a public reputation for environmental sustainability through resource-efficiency measures (e.g. Arla 2011; Volvo 2011; NUON 2014).

Within a meso-level VC, innovative practices can have several sites and roles:

- Water or production chain, as shown in Figure 1: An innovation can upgrade the water-supply chain (e.g. water inputs or WWT, as in the horizontal axis), or else the production chain (e.g. less

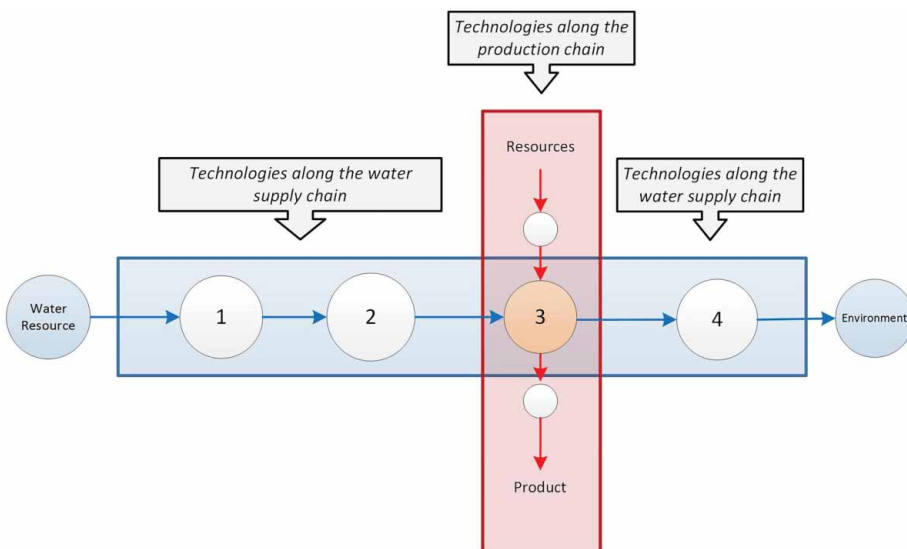


Figure 1. Whole-system (meso-level)VC. Credit: EcoWater project.

Table 1. Resource efficiency through eco-innovation in three case studies.

Resource burdens and potential improvement	Energy input in production process	Energy necessary to reduce hazards in WW	Eco-innovation option
<i>Water-service roles</i> in each case study	In main company	In main and/or WWT company	In main company
<i>Dairy:</i> Milk-powder production extracts milky water needing WWT	Water removal from milk	Treating WW residues to avoid eutrophication	In-house anaerobic WWT slightly reduces overall energy use, while shifting biogas benefits from the outside to dairy company
<i>Trucks:</i> Corrosion-protection needs water to carry inputs, to heat the process baths and to remove wastes	Water abstraction, purification and circulation. Hot water for high-temperature chemical process	Treating pollutants which would cause eutrophication. Removing heavy metals	Silane-based room-temperature process greatly reduces water and energy use; also replaces heavy metals and so avoids hazardous sludge. Lower-volume WW lowers the value added for WWT plant
<i>Cogeneration/CHP</i> (electricity + heat): Plant cooling requires water to remove heat	Water abstraction to cool electricity-condensing point	(Hot cooling-water causes eutrophication, harming aquatic organisms, so it should be minimised.)	District-heating system could use large amounts of waste heat but depends on a large investment, with uncertain long-term return

resource inputs, lower emissions or reuse of wastes, as in the vertical axis). In the diagram, ‘technologies’ is short-hand for innovative practices which depend on more than technologies.

- Process or product: Within the production chain, process upgrading uses resources in more efficient ways, while production-chain upgrading increases the market value of products.

Such roles can have synergies. For example, process upgrading can reduce emissions in wastewater, in turn facilitating improvements in the water-supply chain, for example, through in-house WWT, reuse, recycling, etc.

Eco-efficiency is assessed as a ratio: TVA (income minus costs) is divided by resource burdens, that is, resource inputs and emissions. The assessments adapted mid-point environmental indicators (JRC 2011). A baseline eco-efficiency assessment identified the processes or sites which have the greatest resource burdens and water-based emissions in each case study, for example, in a production plant. These sites became the focus for comparing improvement options with the baseline situation and with each other.

Each case study considered many options for process upgrading and then emphasised one in a multi-stakeholder workshop, as indicated in the subheadings and summarised in Table 1. In the next three sections, each case study starts from the industry-wide context and then focuses on one option. This becomes an entry point to identify tensions and trade-offs within a whole-system production process.

4. Milk-powder production: wastewater pre-treatment option

Dairies have many opportunities for linking economic value with environmental benefits. Initial energy savings have been made with minimal capital investment. Dairies have reduced energy usage for membrane filtration, heating and cooling of products, and spray drying. Some dairies have been ‘reducing the amount of milk that is lost to the effluent stream and reducing the amount of water used for cleaning’, as well as reducing chemical usage (COWI 2000). The UK dairy industry also has been exploring ‘production strategies, processes and equipment to identify and implement innovative and novel technologies in dairy processing’ (Dairy Supply Chain Forum 2011, 18).

Relative to the overall dairy sector, Arla Foods has gone further in adopting and assessing fundamental improvements in water-based processes, which also change a plant's relation with the WWT provider. Arla's plants have already adopted many resource-efficiency measures in plants producing milk powder. The cleaning-in-place systems have been optimised for ensuring milk-powder quality, while also reducing water use and effluent.

There is a substantial transfer of milk ingredients, including large amounts of water, among dairies by lorry. Water extracted from milk is reused in several processes by combining water-storage systems and UV treatment prior to water reuse. Its milk-powder plants also obtain electricity from biogas produced from the company's wastewater sludge as well as from local manure in a local biogas plant. Going further, Arla has taken the lead in water-process improvements, for example, in-house anaerobic digestion of wastewater at some Danish and UK plants (Dairy Roadmap 2013, 49).

Such innovations have been driven by several factors – the company's environmental policy, the company's reputation among consumers, cost-savings and environmental taxes. As extra incentives, the company anticipates higher future costs, restrictions on wastewater discharge due to its salt content and a limited treatment capacity of WW treatment plants. Such drivers have converged in the company's decisions on innovation investment (Nørgaard 2013). Owned by farmers and accountable to their representatives, the company aims to counter the recent trend towards lower farm-gate milk prices (Arla Foods 2013, 3).

Since at least 2008 the company has promoted its overall policy direction as 'Closer to Nature', emphasising its commitment to environmentally sustainable methods. Its Environmental Strategy 2020 includes various targets for resource conservation, for example, reducing GHG emissions by 25% in production and transport, and reducing energy and water consumption in production by 3% every year (Arla Foods 2011). It aims to reduce energy, water and chemicals usage, as well as the amount of waste water by 25% per kg powder (2011–2014), through process optimisation (Hansesgaard 2013).

Arla Foods own approx. 40% of dairies in Denmark and many abroad, especially resulting from an expansion policy (Arla Foods 2013, 2). EU milk quotas may be relaxed, thus increasing the supply, yet extra milk products cannot be sold on a static European market. Given those limits, Arla's expansion aims to export high-quality or specialty milk powder. But its production requires enormous energy to extract water from milk.

In such ways, Arla Foods have been undergoing a restructuring, which may result in fewer and larger dairies. Greater concentration poses the issue of cleaner production: whether or how the process design should internalise and/or recycle resource flows among production units. The company has been adopting or considering major changes in the production process.

Turning wastewater sludge into biofertiliser would be more eco-efficient than conversion to biogas. This innovation would need to expand the meso-level through farmers as users of the biofertiliser. But the company has not pursued this prospect; instead, it has focused on options to bring functions in-house.

Arla Foods' potential future changes interested all stakeholders in the EcoWater assessment of meso-level eco-efficiency. The EcoWater case study initially focused on Arla's Holstebro HOCO plant, which processes milk into various protein-specific powders. It has been paying a WWT company which anaerobically extracts biogas, substituting for fossil fuels in district heating. HOCO is considering several in-house options to reduce demand for water and energy, especially in-house anaerobic pre-treatment of wastewater. This option would change the resource burdens as follows:

- Production of biogas to substitute natural gas → reduced fossil-fuel depletion and CO₂ emissions.
- Reduced load on WWT plant → reduced power consumption and CO₂ emissions.
- Reduced biogas production → reduced downstream power and heat production (Andersen 2013).
- So the downstream system would need more fossil fuels than before, thus counteracting the upstream gains.

Table 2. Comparing baseline with anaerobic digestion: difference in meso-level environmental impacts (EcoWater 2015a, Tables 4 and 5, 78).

Mid-point impact Category	Baseline environmental performance	Anaerobic digestion pre-treatment option
Climate change (kgCO _{2eq} /kg milk)	58	52
Freshwater resource depletion (m ³ /kg)	0.008	0.008
Eutrophication (kgPO _{4-eq} ³ /kg)	1.7	1.7
Human toxicity (kg1,4DCB _{eq} /kg)	0.06	0.06
Acidification (kgSO _{2eq} /kg)	0.56	0.56
Aquatic ecotoxicity (kg1,4DCB _{eq} /kg)	0.002	0.002
Terrestrial ecotoxicity (kg1,4DCB _{eq} /kg)	0.003	0.003
Photochemical ozone formation (kg C ₂ H _{4eq} /kg)	0.0005	0.0005

From a whole-system perspective on resource efficiency, the in-house WWT option offers an approx. 11% reduction in the mid-point indicator for climate change, with no other improvement (see Table 2). By contrast to this modest reduction, a micro-level focus on the company's internal processes would imply a greater improvement towards the company's environmental targets. Thus, this analysis reveals a tension between micro-level (company) versus macro-level (whole-system) improvement in resource efficiency.

Having provided essential information for the assessment, stakeholder companies attended a workshop to discuss the implications. The whole-system perspective raised doubts about the specific option for WW pre-treatment. The perspective attracted stakeholders' interest for assessing other options in order to evaluate their relative benefits (EcoWater 2015a).

5. Truck-body corrosion-resistance: silane-based option

The automobile sector has generally directed eco-innovation at vehicle use and users, especially for greater fuel efficiency as a competitive advantage, as well as CO₂ reductions as a regulatory criterion (e.g. Oltra and Mäider 2009). The sector has incrementally improved the energy efficiency of the internal combustion engine. Since the 1990s, some manufacturers have also developed alternative-fuel vehicles (Sierzchula et al. 2012; Köhler et al. 2013).

Such redesign has responded partly to market competition; vehicles can generally gain a higher price or sales through fuel efficiency, but not through improvements in the production process. In the European context, greater fuel efficiency has been stimulated by legislation requiring that by 2015 CO₂ emissions from all new EU-registered cars should not exceed an average of 130 g CO₂/km across the range of each manufacturer; this limit was around one-fifth below 2007 levels (EC 2009). Moreover, car manufacturers receive official recognition and carbon credits if they fit their new cars with approved 'eco-innovations' (EC 2011).

As an atypical priority within the industry, Volvo's agenda for resource efficiency has driven improvements within the production process. According to the Volvo Group's sustainability report, 'a resource-efficiency approach is well integrated in our culture and is an important priority ahead' (Volvo 2011, 38). Operations attempt to minimise energy use and recycle materials, especially by installing closed-process water systems (Volvo 2011, 58).

At each Volvo site, different units have responsibility for economic and environmental evaluation, with some discussion between them. There has been no systematic discussion between Volvo and WWT companies about improvement options. So fragmented responsibilities impede or complicate whole-system improvements.

In the corrosion-protection process, Volvo Trucks has already made an environmental improvement by replacing a hazardous chromium process with zinc-phosphating technology. But the latter still has several environmental disadvantages: it requires heating of process baths, uses heavy metals (Zn, Ni and Mn) which end up in wastewater, and produces hazardous sludge (e.g.

Table 3. Comparing baseline with silane-based treatment: difference between meso-level environmental impacts (EcoWater 2015a, Tables 5–13, 104).

Mid-point impact category	Baseline environmental performance	Silane-based option at Tuve plant
Climate change (tCO ₂ eq)	652	642
Freshwater resource depletion (m ³)	1659	1640
Eutrophication (kgPO ₄ eq)	691	662
Human toxicity (kg _{1,4} -DBeq)	14,467	14,136
Acidification (kgSO ₂ eq)	1913	1799
Abiotic resource depletion (kgSbeq)	1008	995
Aquatic ecotoxicity (kg _{1,4} -DBeq)	16,404	14,677
Stratospheric ozone depletion (kgCFC-11eq)	0.62	0.61
Terrestrial ecotoxicity (kg _{1,4} -DBeq)	228	225
Photochemical ozone formation (kgC ₂ H ₄ eq)	129	121

metal hydroxides). Relative to those problems, a new silane-based polymer has several advantages illustrating less ‘energy for water’. It features: process at room temperature; total energy use ~40% less than the Business As Usual (BAU) process; water use 50–90% less than BAU; no use of heavy metals or P; no hazardous sludge and very little other sludge. Wastewater pollutants (Zr, silane and fluoride) can be reduced to ~0 mg/l by ion exchange.

Looking beyond the site, silane-based technology was evaluated at the meso-level by linking the company’s process with the water supplier and Stena Recycling, which charges Volvo for WWT services. The silane-based option would reduce water use, as well as the wastewater quantity and emissions content. Improvements in mid-point indicators would be modest – as the most significant, aquatic ecotoxicity would have an 11% improvement. The next greatest improvements (photochemical ozone formation, acidification and eutrophication) would be only 5–6% each (Table 3).

As regards the TVA, the total costs of water-related inputs would be somewhat reduced for all three companies (Volvo, its water supplier and WWT) because the lower quantity of both water use and WWT mean a lower electricity demand for pumps and less use of chemicals. So, the TVA slightly rises through lower costs for water input. More significantly, the TVA would be redistributed across the meso-level VC: the WWT company would lose value added. So, the silane-based option involves a financial trade-off among actors.

The multi-stakeholder workshop discussed benefits, drivers and barriers for the silane-based option. Participants agreed: ‘If Volvo improved its environmental performance and generated effluents of better quality, it would be easier for Stena Recycling to comply with the regulations’ (EcoWater 2013, 35). More generally, participants agreed, Volvo should avoid sub-optimal solutions:

Sub-optimisation can be more easily avoided through stakeholder cooperation in evaluating the overall system. Organization of the different ‘players’ towards a common goal can increase cooperation among actors that perhaps unknowingly share a mutual interest in environmental protection. (EcoWater 2013, 37–38)

Although optimal meso-level solutions can result from cooperation among stakeholders, their economic interests may conflict. In the example here, such tensions arise from a change which clearly enhances eco-efficiency within the company. Moreover, this option offers only a modest improvement through incremental eco-innovation, continuing a path dependence within road transport.

6. Cogeneration: district-heating option

Energy cogeneration, also known as CHP (Combined Heat and Power), has higher energy efficiency than separate production of each component, provided that there is adequate demand for both power and heat. CHP plants have been established mainly in markets with large heat demand, especially in energy-intensive industries, greenhouse horticulture, services in large buildings and

residential areas. The latter use depends on a large-scale, long-term expensive investment in district-heating systems.

A key factor in useable heat is the use time, that is, the time-period when thermal energy is consumed. Domestic heat demand varies over the day and with the seasons; demand exists only during 30–50% of the year, and peak demand occurs only a few days per year. During the rest of the year, most of the produced heat remains waste heat, typically discharged to surface water. Given this constraint, greater resource efficiency depends on a flexible distribution network and/or peak-shaving capacity to lower the maximum demand.

Another key factor in useable heat is its temperature. Industrial purposes, which are often year-round businesses, require very high temperatures. District heating typically uses distribution temperatures of about 100–120°C, while some developments use a lower temperature, such as greenhouse farming.

Cogeneration involves trade-offs between electricity and heat: Maximising power production requires the lowest possible temperature at the condensing site of the generator, but this depends on greater water-tapping (cooling), thus generating more excess heat (Verbruggen et al. 2013, 578). Conversely, tapping water at higher temperatures yields hotter heat and reduces heat in cooling water, though it somewhat reduces the useful electrical power and thus the related income (Figure 2). The latter option has extra disadvantages: investment in different equipment would be necessary to tap electricity at a higher temperature, as well as to transmit the hotter heat.

From a micro-level perspective, for example, an energy plant per se, the priority is to maximise income (or profit), which comes mainly from electricity as the most lucrative product. From a meso-level (whole-system) eco-efficiency perspective, by contrast, priorities are to maximise usable energy and consequent income while also minimising resource burdens, especially fossil-fuel demand, GHG emissions, cooling-water emissions, etc. Any mismatch between heat demand and production can be mitigated by various strategies, for example: buffer basins and additional heat-only boilers can shave daily peaks, and the system can include other heat users with a more constant demand.

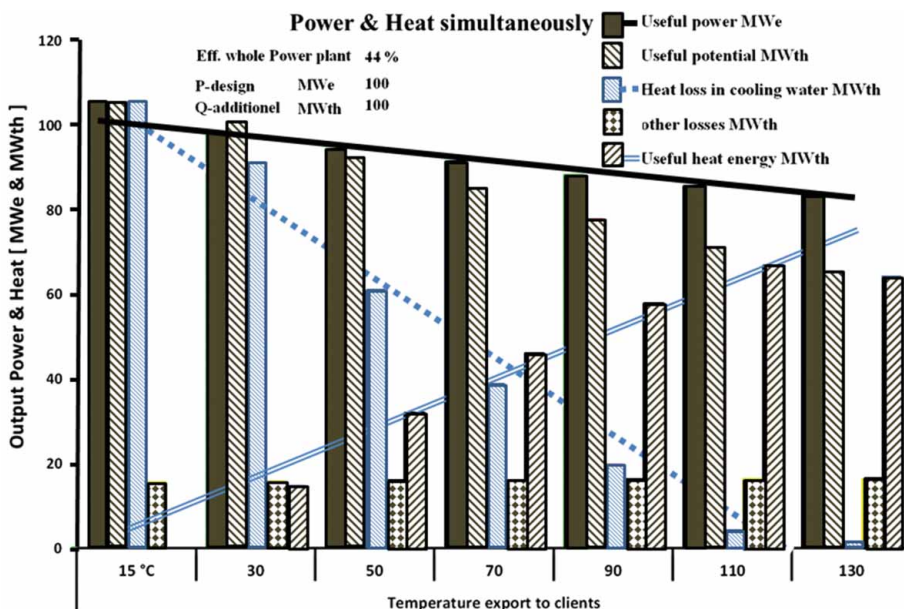


Figure 2. Effects of thermal energy distribution at different temperatures on power-generation efficiency and useful thermal energy. Credit: Deltares, Amsterdam/EcoWater.

In the Netherlands the main cogeneration company plans to expand heat supply to district heating, alongside heat-storage facilities to provide peak-shaving amidst intermittent demand:

Expanding further in district heating projects also provides valuable opportunities to expand further in renewable energy, as district heating provides a significant reduction of CO₂ emissions in comparison with conventional gas-heated boilers ... District heating fits well with Nuon's strategy, since it offers a 50% to 80% reduction of CO₂ emissions compared to conventional gas-heated boilers, depending on the source of the heat. (NUON 2014, 7, 11)

The EcoWater study focused on a cogeneration plant supplying mainly residential areas in Amsterdam and Almere. Amsterdam municipality has made a commitment to increase district heating (Gemeente Amsterdam 2013), though specific support measures remain unclear. A thermal network for district heating offers advantages in resource efficiency, for example, by substituting the waste heat for fossil fuels, but incurs extra investment costs of retrofitting houses (EcoWater 2015a, 70–72).

The EcoWater study's multi-stakeholder workshop discussed the necessary conditions for establishing a thermal network in the local context. District-heating systems had been installed in a newly built neighbourhoods in the Netherlands (and elsewhere), but there was little residential building activity near the plant; so this solution would replace and/or jeopardise previous investment in heating systems.

The workshop also discussed drivers and barriers of various improvement options. Some key points from the discussion: The company's commitment to extend district heating would need political confidence in future favourable conditions, especially through 'consistent governance for a 30–50 year period'. Amongst such conditions for such investment: a thermal network needs a price equal to gas-based heat; and CO₂ emission credits need to be made more expensive, so that low-carbon energy becomes more competitive (Goossens and Meijer 2014).

Under foreseeable circumstances, the company will not make a priority of reducing the electricity–heat ratio to yield higher temperature heat, nor of linking the plant with a district-heating system. More modest options have been pursued. Year-round demand for heat would help, especially from industrial users, so these have been sought. Peak shaving of daily peaks (via a heat buffer or storage facility) would reduce the temporal mismatch between demand and supply of electricity. This small investment offers a relatively modest improvement in resource efficiency and GHG savings, while also significantly lowering costs. When it becomes operational at the Diemen 33 plant, the peak-shaving facility will reduce use of the combined cycle combustion turbine or heat-only boilers during the daily peak demand for heat.

The above comparisons reveal tensions between resource efficiency at the micro-level (company) and meso-level (whole system). From the latter perspective, resource efficiency would be greatly improved by a thermal network using all the waste heat; but this would depend on expensive long-term investment and elusive heat users, as well as less income from electricity production. This helps to explain why the EC Cogeneration Directive 'failed to fully tap the energy-saving potential' of CHP (CEC 2011c), as acknowledged by the European Commission. These obstacles warrant attention in order to fulfil EU policy on expanding district heating (EC 2012, 6).

7. Conclusion: tensions in whole-system value-chain assessments

Many companies have invested in eco-innovation, combining environmental and economic benefits. Production processes have been upgraded in ways that enhance a company's environmental reputation. Such change has been generally evaluated within a company's internal process, thus neglecting value-chain changes which may affect other companies' income and wider resource burdens. Looking more broadly, some companies have shown interest in assessment at the whole-system (meso) level of a production process. A meso-level assessment can inform efforts to internalise more environmental externalities through eco-innovation. From such a perspective, this Conclusion answers the original three questions in turn.

7.1. Whole-system tensions in process upgrading

What tensions arise among various aims and benefits of eco-innovation? Our EC research project operationalised the meso-level through comparative eco-efficiency assessments. The project gained cooperation from case-study companies (motor vehicle, dairy and cogeneration) which already had invested in process eco-innovation. They have strong prospects for upgrading the production process, relative to their respective industrial sector. Such investment has multiple incentives – environmental objectives, ‘green’ reputation, lower energy costs and future regulatory requirements.

Relevant stakeholders provided essential information on the baseline context and on eco-innovation options that they were considering for investment, so that the case-study team could assess their whole-system eco-efficiency. The method assessed changes in resource burdens and TVA across a meso-level VC, for example, encompassing water suppliers, water users and wastewater treatment (WWT) providers. Comparative assessments informed multi-stakeholder workshop discussions of options, drivers and barriers.

Focusing on specific options, the assessments identified many tensions – among various aims, resource burdens, process stages, system levels, economic beneficiaries and timescales. For a project-wide overview of ‘Eco-innovation win-win or trade-offs?’, see the cross-case comparative report (EcoWater 2015b, 21). Such tensions complicate the concept of eco-innovation as ‘enabling win-win synergies’ (OECD 2012; cf. Kemp and Oltra 2011; Horbach, Rammer, and Rennings 2012, 113).

7.2. Internalising externalities within limits

What is the scope to internalise externalities, within what limits? The three case studies (Table 1) illustrate the above tensions, especially the systemic limits of internalising externalities.

- (i) A dairy company plans to expand European milk-powder production for global export. It has set ambitious targets to lower resource burdens annually, thus facing contradictory objectives for eco-innovation. A shift to in-house WWT treatment would substitute some renewable energy for fossil fuels and so enhance the dairy’s internal resource efficiency, but such benefits would be largely shifted from the outside to the inside the dairy, offering only modest meso-level benefits. Turning wastewater sludge into biofertiliser would be a more eco-efficient way to use WW but has not been explored.
- (ii) For truck-body corrosion-resistance, a novel technological process would lower resource burdens and enhance the company’s sustainability reputation. In the overall VC, the WWT company would lose income, thus creating conflict over the distribution of benefits. The environmental improvement would be modest (at most 6%, with one exception), for an incremental change within the incumbent road-transport regime.
- (iii) A cogeneration plant seeks ways to turn its excess-heat problem into an environmental and economic benefit. A change in the production process could supply hotter heat to industrial users, but the change brings financial disadvantages. A district-heating system would have greater benefits in resource efficiency, but such investment faces obstacles from institutional fragmentation and long-term policy uncertainty. And the cogeneration plant faces a financial trade-off between generating more flexibly usable heat versus the more lucrative electricity. At present the company is adopting a heat-storage facility alone to avoid electricity and heat generation during periods of low electricity prices, offering only a modest improvement in resource efficiency.

As those cases illustrate, the institutionally most feasible or attractive eco-innovations are incremental, offering modest improvement within an industrial path dependence. By contrast, radical

eco-innovation needs path creation through extra value-chain actors, functions and resource usages which can provide greater overall benefits (Carrillo-Hermosilla, del Río, and Könnölä 2010; De Marchi, Di Maria, and Micelli 2013). As in examples above, extra functions need industrial symbiosis (De Simone and Popoff 2000; Chertow 2007).

Such a systemic change faces many obstacles. More generally, improvement options entail tensions and trade-offs – among various aims, resource burdens, process stages, system levels, economic beneficiaries and timescales. These tensions may limit the scope to internalise environmental externalities for the common good through radical innovation (cf. Bleischwitz 2003).

7.3. EU policy implications for lower resource burdens

What are implications for EU policy frameworks? The EU has had a commitment to technoscientific eco-innovation as the primary means to lower resource burdens. Various financial incentives and regulations have aimed to stimulate such technological innovation and adoption. In particular, the Lisbon agenda sought greater R&D investment to make Europe ‘the globally most competitive knowledge-based economy by 2010’ (EU Council 2000).

The Europe 2020 strategy promotes ‘resource efficient technologies’ to decouple economic growth from the use of resources (CEC 2010, 4; also CEC 2011a, 2011b). For the current decade, the shift towards a resource-efficient and low-carbon economy ‘will help us to boost economic performance while reducing resource use’. In particular, ‘stricter environmental targets and standards which establish challenging objectives and ensure long-term predictability, provide a major boost for eco-innovation’ (CEC 2011a, 2, 6).

During the Lisbon Agenda decade, however, Europe increased its per capita materials consumption, even apart from indirect consumption through imports:

The European economy grew by 35% between 2000 and 2007, but also material consumption increased in absolute terms (7.8%), almost three times the growth in European population (2.6%). The absolute growth in material consumption indicates that the EU did not achieve an absolute decoupling, but only a relative decoupling. (EIO 2011a, 14)

The consumption increase has had many drivers, for example, resource efficiency generating a rebound effect, and a financialisation agenda diverting investment from process improvements (e.g. Jackson 2009; Birch and Mykhenko 2014).

Apparently eco-innovation has had a weak role in counteracting the EU’s increase in resource burdens. As highlighted by the earlier literature survey, some limitations are also illustrated by our case studies of prospective eco-innovation: the most institutionally attractive forms are incremental, remaining within a path dependence. The tensions and difficulties cast doubt on an EC strategy emphasising uptake of eco-innovative technologies as the means to decouple economic growth from resource burdens. Under foreseeable circumstances, there seems an elusive prospect for eco-innovation alone to provide a significant increase in resource efficiency, much less an absolute decoupling of economic growth from resource burdens.

As a way forward, appropriate policy frameworks could incentivise radical innovations, especially through industrial symbiosis. For prioritising policy support amidst multiple options, whole-system assessments could help to identify relative benefits and potential trade-offs of radical innovations.

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References

- Andersen, M. 2013. "The EcoWater Approach Applied to Arla HOCO." PPT presentation at EcoWater workshop, Arla HOCO, Holstebro, September 20.
- Arla Foods. 2011. *Environmental Strategy 2020*. Accessed March 26, 2014. <http://www.arla.com/Sustainability/Environment-strategy>.
- Arla Foods. 2013. *Our Responsibility: Arla Foods' Corporate Social Responsibility Report*. Accessed March 26, 2014. http://www.arla.com/Images/arla.com/PDF/CSR/2012/ENG_2012.pdf.
- Birch, K., and V. Mykhenko. 2014. "Lisbonizing Versus Financializing Europe? The Lisbon Agenda and the (un)Making of the European Knowledge-Based Economy." *Environment and Planning C: Government and Policy* 32: 108–128.
- Bleischwitz, R. 2003. "Cognitive and Institutional Perspectives of Eco-Efficiency." *Ecological Economics* 46: 453–467.
- Carrillo-Hermosilla, J., P. del Río, and T. Könnölä. 2010. "Diversity of Eco-Innovations: Reflections From Selected Case Studies." *Journal of Cleaner Production* 18: 1073–1083.
- CEC. 2010. *Europe 2020: A Strategy for Smart, Sustainable and Inclusive Growth*. Brussels: Commission of European Communities.
- CEC. 2011a. *A Resource-Efficient Europe: Flagship Initiative Under the Europe 2020 Strategy*. Brussels: Commission of European Communities.
- CEC. 2011b. *Innovation for a Sustainable Future: The Eco-Innovation Action Plan (Eco-AP)*. Brussels: Commission of European Communities.
- CEC. 2011c. *Proposal for a Directive of the European Parliament and of the Council on Energy Efficiency and Repealing Directives 2004/8/EC and 2006/32/EC SEC(2011) 779 final SEC(2011) 780 final*. Brussels: Commission of European Communities. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0370:FIN:EN:PDF>.
- Chertow, M. 2007. "'Uncovering' Industrial Symbiosis." *Journal of Industrial Ecology* 11 (1): 11–30.
- COWI. 2000. *Cleaner Production Assessment in Dairy Processing*. Prepared by COWI Consulting Engineers and Planners AS, Denmark, for UNEP Division of Technology, Industry and Economics and Danish EPA. <http://www.unep.fr/shared/publications/pdf/2480-CpDairy.pdf>.
- Dairy Roadmap. 2013. *Dairy Roadmap: Environmental Sustainability Report 2013*. <http://www.dairyco.org.uk/resources-library/research-development/environment/dairy-roadmap-2013/>.
- Dairy Supply Chain Forum. 2011. *Dairy Roadmap: Our Route towards Environmental Success*. Kenilworth: Dairy Supply Chain Forum's Sustainable Consumption and Production Taskforce.
- De Marchi, V., E. Di Maria, and S. Micelli. 2013. "Environmental Strategies, Upgrading and Competitive Advantage in Global Value Chains." *Business Strategy and the Environment* 22: 62–72.
- De Simone, L., and F. Popoff. 2000. *Eco-Efficiency: The Business Link to Sustainable Development*. Cambridge, MA: MIT Press.
- EC. 2009. "Regulation 443/2009 of the European Parliament and of the Council of 23 April 2009 Setting Emission Performance Standards for new Passenger Cars as Part of the Community's Integrated Approach to Reduce CO₂ Emissions From Light-Duty Vehicles." *Official Journal of the European Union L* 140: 1–15.

- EC. 2011. "Commission Implementing Regulation (EU) No 725/2011 of 25 July 2011 Establishing A Procedure for the Approval and Certification of Innovative Technologies for Reducing CO₂ Emissions From Passenger Cars Pursuant to Regulation (EC) No 443/2009 of the European Parliament and of the Council Text with EEA Relevance." *Official Journal of the European Union* L 194: 19–24.
- EC. 2012. "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC." *Official Journal of the European Union* L 315: 1–56.
- EcoWater. 2013. *D6.1 Synthesis Report from the 1st Round of Case Study Events*. http://environ.chemeng.ntua.gr/ecoWater/UserFiles/files/D6_1_Final%281%29.pdf.
- EcoWater. 2015a. *Deliverable 4.4: Technology Assessment and Scenario Analysis*. <http://environ.chemeng.ntua.gr/ecoWater/UserFiles/files/D4%204%20Technology%20assessment%20and%20scenario%20analysis.pdf>.
- EcoWater. 2015b. *Deliverable 5.2: Cross-Comparison of Case-Study Outcomes*. http://environ.chemeng.ntua.gr/ecoWater/UserFiles/files/D5_2%20Cross%20Comparison%20of%20CS%20Outcomes.pdf.
- EIO. 2011a. *Eco-Innovation Challenge: Pathways to A Resource Efficient Europe*. Brussels: Eco-Innovation Observatory (EIO). Funded by the European Commission, DG Environment.
- EIO. 2011b. *Water Innovation: How Eco-Innovation can Contribute to the Sustainability of Europe's Water Resources*. Brussels: Eco-Innovation Observatory (EIO). Funded by the European Commission, DG Environment.
- EU Council. 2000. *An Agenda of Economic and Social Renewal for Europe: (aka Lisbon Agenda)*. Brussels: European Council, DOC/00/7.
- Garud, R., A. Kumaraswamy, and P. Karnøe. 2010. "Path Dependence or Path Creation?" *Journal of Management Studies* 47 (4): 760–774.
- Gemeente Amsterdam. 2013. Kennisnemen van de voorgenomenuitbreiding van het Amsterdamsestadswarmtenetnaar de bestaandebouw [Proposed Expansion of Amsterdam's District Heating to Existing Buildings], July 2. <http://zoeken.amsterdam.raadsinformatie.nl/cgi-bin/showdoc.cgi?action=view/id=206750/type=pdf/raadsbesluit.189.663.3a.13.pdf>.
- Goossens, H., and K. Meijer. 2014. Causal Loop and Group Model-Building Session: Summary, EcoWater Case Study 6: Cogeneration of Heat and Power, held on 7 November 2013. Amsterdam: Deltares.
- Hansesgaard, K. 2013. PPT presentation at EcoWater workshop, Arla HOCO, Holstebro, September 20.
- Horbach, J., C. Rammer, and K. Rennings. 2012. "Determinants of Eco-Innovations by Type of Environmental Impact: The Role of Regulatory Push/Pull, Technology Push and Market Pull." *Ecological Economics* 78: 112–122.
- Huppes, G., R. Kleijn, R. Huele, P. Ekins, B. Shaw, M. Esders, and S. Schaltegger. 2008. *Measuring Eco-Innovation: Framework and Typology of Indicators Based on Causal Chains*. Final Report of the ECODRIVE Project, CML, University of Leiden. http://www.eco-innovation.eu/wiki/images/Ecodrive_final_report.pdf.
- Jackson, T. 2009. *Prosperity Without Growth: Economics for A Finite Planet*. London: Earthscan.
- Jansson, J. 2011. "Consumer Eco-Innovation Adoption: Assessing Attitudinal Factors and Perceived Product Characteristics." *Business Strategy and the Environment* 20: 192–210.
- JRC. 2011. *International Reference Life Cycle Data System (ILCD) Handbook: Recommendations for Life Cycle Impact Assessment in the European Context*. 1st ed. Luxembourg: Publication Office of the European Union. European Commission, Joint Research Centre, Institute for Environment and Sustainability.
- Kemp, K., and V. Oltra. 2011. "Research Insights and Challenges on Eco-Innovation Dynamics." *Industry and Innovation* 18 (3): 249–253.
- Kemp, R., and J. Rotmans. 2005. "The Management of the Co-Evolution of Technical, Environmental and Social Systems." In *Towards Environmental Innovation Systems*, edited by M. Weber and J. Hemmelskemp, 33–55. Berlin: Springer.
- Köhler, J., W. Schade, G. Leduc, T. Wiesenthal, B. Schade, and L.T. Espinoza. 2013. "Leaving Fossil Fuels Behind? An Innovation System Analysis of Low Carbon Cars." *Journal of Cleaner Production* 48: 176–186.
- Michelsen, O., A. M. Fet, and A. Dahlsrud. 2006. "Eco-Efficiency in Extended Supply Chains: A Case Study of Furniture Production." *Journal of Environmental Management* 79 (3): 290–297.
- Nørgaard, R. 2013. PPT presentation at EcoWater workshop, Arla HOCO, Holstebro, September 20.
- Nuon. 2014. *N.V. Nuon Energy Annual Report 2013: Continued Positioning for Tomorrow's Energy Market*. <http://www.nuon.com/Global/Nederlands/Financials/Jaarverslagen/Nuon%20Jaarverslag%202013.pdf>.
- OECD. 2012. *The Future of Eco-Innovation: The Role of Business Models in Green Transformation*. <http://www.oecd.org/innovation/inno/49537036.pdf>.
- Oltra, V., and S.-J. Maïder. 2009. "Sectoral Systems of Environmental Innovation: An Application to the French Automotive Industry." *Technological Forecasting and Social Change* 76 (4): 567–583.
- Reid, A., and M. Miedzinski. 2008. *Eco-Innovation: Final Report for Sectoral Innovation Watch*. Brussels: Technopolis.
- Rennings, K., and C. Rammer. 2011. "The Impact of Regulation-Driven Environmental Innovation on Innovation Success and Firm Performance." *Industry and Innovation* 18 (3): 255–283.
- Schenk, N. J., H. C. Moll, and A. Uiterkamp. 2007. "Meso-Level Analysis, the Missing Link in Energy Strategies." *Energy Policy* 35: 1505–1516.
- Sierczula, W., S. Bakker, K. Maat, and B. van Wee. 2012. "Technological Diversity of Emerging Eco-Innovations: A Case Study of the Automobile Industry." *Journal of Cleaner Production* 37: 211–220.

- Van Caneghem, J., C. Block, P. Cramm, R. Mortier, and C. Vandecasteele. 2010. "Improving Eco-Efficiency in the Steel Industry: The Arcelor Mittal Gent Case." *Journal of Cleaner Production* 18 (8): 807–814.
- van den Bergh, J., B. Truffer, and G. Kallis. 2011. "Environmental Innovation and Societal Transitions: Introduction and Overview." *Environmental Innovation and Societal Transitions* 1 (1): 1–23.
- Verbruggen, A., P. Dewallef, S. Quoilin, and M. Wiggan. 2013. "Unveiling the Mystery of Combined Heat & Power (Cogeneration)." *Energy* 61: 575–582.
- Volvo. 2011. *Sustainability Report 2010*. Göteborg: Volvo Group.
- Wagner, M., and P. Llerena. 2011. "Eco-Innovation Through Integration, Regulation and Cooperation: Comparative Insights From Case Studies in Three Manufacturing sectors." *Industry and Innovation* 18 (8): 747–764.
- WBCSD. 2000. *Eco-Efficiency: Creating More Value with Less Impact*. Geneva: World Business Council for Sustainable Development.
- Welford, R. 1998. "Editorial: Corporate Environmental Management, Technology and Sustainable Development: Postmodern Perspectives and the Need for A Critical Research Agenda." *Business Strategy and the Environment* 7 (1): 1–12.