

Waste Incineration for the Future

Scenario analysis and action plans

IEA Bioenergy



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Preface

This report is a deliverable from a project within the Swedish Strategic Innovation Program RE:Source, financed by the Swedish Energy Agency, Formas and Vinnova. The project, Waste Incineration for the Future, aims to produce a knowledge base for the development of energy recovery from waste that suits the future circular economy. In order to identify and prioritize relevant innovations, a scenario process has been undertaken with stakeholders from the energy, waste and recycling, and manufacturing industries. The result is two distinct, complementary scenarios for the circular economy in Sweden, each with different implications for innovation in waste incineration and energy recovery.

With these scenarios as a starting point, the project has defined prioritized areas for innovation and produced action plans for promoting innovation.

Apart from the financing of the RE:Source program, the project also received financial support from the Swedish industry body for waste management and recycling, Avfall Sverige. The following organizations also contributed through participation in workshops and surveys and through feedback on written reports:

- Avfall Sverige
- Elkretsen
- Energiföretagen Sverige
- Energimyndigheten
- EON
- Fiskeby Board
- Fortum Waste Solutions
- FTI AB
- Gästrike Återvinnare
- Göteborgs Stad Kretslopp och Vatten
- Högsolan i Borås
- Mistra Future Fashions
- Profu
- Ragn Sells
- Renova
- RISE Research Institutes of Sweden
- SRV Återvinning
- Stena Recycling
- Stockholm Exergi (fd. Fortum värme)
- Sveriges Bygginndustrier
- Sysav Utveckling
- Tekniska verken i Linköping
- Umeå Energi
- Vattenfall
- ÅF
- Återvinningsindustrierna

Scenarios

The following narratives describe two different configurations of a future circular economy in Sweden, and the journey that led there. The scenarios are not predictive, but should function as discrete, complementary pictures of developments with important consequences for waste incineration. Some overlap between them exists, but the scenarios are based on different fundamental logics and have different implications.

In Scenario 1, **Sustainable Consumption**, the circular economy in Sweden is founded on new consumption patterns and circular business models (e.g. servitization, functionalization). In this scenario products live longer lives and go through multiple use cycles before they reach the waste management and recycling sectors. The role of waste incineration is primarily to deal with products and materials that are more complex and difficult to recycle than today's – which make up a significant part of the goods reaching the end of their use phases.

In Scenario 2, **Deep Recycling**, the circular economy in Sweden is founded on recycling that is built into the foundations of the economy, and waste incineration is a part of a socio-technical system wherein secondary raw material supply, material and chemical recycling, and energy recovery are deeply integrated. Incineration is important for handling a comparatively small part of material flows, and new and specialized business models have been developed for a variety of configurations.

Accompanying the narratives are figures illustrating how two different product categories travel through the "value circle" in each scenario.

SCENARIO 1: SUSTAINABLE CONSUMPTION

In this scenario the sharing, leasing and lending of products is extensive and product life spans have lengthened, and the flow of material to waste management and recycling sectors has been significantly decreased. On the other hand these flows include an increasing share of products and materials that are difficult to handle due to complex designs for durability and advanced functionality, and a significant amount of material cannot be recycled and is thus incinerated. Waste incinerators make money from energy sales but also from decontamination, extracted metals, minerals and construction materials. This situation requires new techniques for separating streams into their plants.

In 2045 Sweden is in the midst of a major transition: from the linear economy that dominated the world after the industrial revolution, towards a circular economy, where the value in the earth's resources is increasingly preserved within the economy. By this point the transition has come so far, and has been such a large part of everyday reality for so many, that there are few Swedes who notice the changes anymore. In less than two generations' time Swedes have fundamentally changed their views on what they want to buy and own, what they want sold as product and what they prefer as a service, and what happens to a product when they are done using it.

The transition took off with Generation Z, the young people of the late 2010s who took for granted that as much as possible needed to be done to protect the environment and save natural resources, and who understood early that their economic activities had significant ethical and political dimensions. These views grew stronger in the next generation, where children were educated from pre-school age about the downsides of traditional linear models of consumption and disposal. By 2030 there was hardly anyone under 30 who didn't share these fundamental values.

But these young people were not monks and ascetics. Just like their parents they valued newness

and excitement, and even more than their parents, they sought to differentiate and profile themselves in, to stand out and acquire status in a range of social contexts, in part through the things they bought and used. They saw no conflict between this desire and their environmental awareness and ethics.

In the beginning of the 2020s many companies also began to see that this was not a conflict of interests but rather a new market. Those who created new products that lived up to these new consumers' expectations – products that were durable, that could be upgraded without being replaced, that could both be personalized and shared with others – became the hottest brands in their categories. Dealers and brokers soon emerged to work with both sharing and customization, so that more and more products became part of a service, wherein the customer bought customized functions, appearances, and rights of use and access. Soon the "wow factor" in these arrangements was gone, and by 2030 functionalization and sharing services are common across most product categories, from cars to furniture to leisure and sporting equipment and toys. By 2035 these business models have outgrown traditional product ownership models.

These new business models even spread to single-use products like food, paper and other traditionally "disposable" products. More and more people subscribe to food as a service, where tailored combinations are delivered home for preparation. Subscribers see both personalization and decreased spoilage and wasted packaging as obvious benefits of these offerings, and this in turn effects presentation of these products in shops, with bulk/loose/unpackaged foods available across more and more categories. The 2030s see the emergence of many innovations in packaging that can be re-used and re-sized to suit different volumes, shapes, and consistency of their contents.

The changes began with consumers and new business models but quickly placed new demands on design and production of goods. Product and service designers began to think about their use cases in completely new ways. Both physical durability and the durability of the product's value soon became the keys to successful offerings. That materials, surfaces and components were built to last became fundamental requirement, as sharing of products and function/service-based offerings increased the degree of utilization for almost all parts and components. New composite materials were developed to suit multiple use cases and environments. Since more manufacturers and retailers now retained product ownership, they were incentivized to create durable and flexible products, often based on platform solutions.

The most successful products of 2045 are those whose value lasts the longest and serves the most users. More and more products – from heavy goods such as vehicles and furniture to lighter goods like toys and clothes – are designed to facilitate customization and even personalization by the user. Flexible design and construction means that those who lease, rent, and share can update the appearance and function of their products in shorter and shorter cycles, without the product needing to be disposed of or manufactured again. For complex products and functions, remanufacturing and repairs play an important role, but for many products an increasing amount of customization can be done directly by the user. The consumer culture has become one where sharing and personalization happens both within the retail sector and outside of it, in social interactions between users.

By 2045 such models are not just part of a growing trend – they account for the bulk of consumption in Sweden. The result is major changes in the flows of material resources. Complex products circulate many times among multiple users, repairs, and remanufacturers. That which is classified as new production has decreased across many sector, and domestic demand for primary raw materials is continuing to fall. Nonetheless the Swedish economy is growing, as innovation in product and service design keeps productivity high.

Waste does not disappear: despite design for durability and increasing circulation, products and components do still wear out eventually. The flow to traditional waste management and recycling processes has decreased, and has new characteristics. New design solutions customized for the use phases create difficulties as products reach their end of life. Construction for personalization and product customization do not facilitate dismantling, and separation of layers and components can require (sometimes prohibitively) expensive processes to be developed. Complex composite materials make material recycling difficult and at times impossible.

These complications are further worsened by the sensors and microelectronics embedded in almost all non-food products. Sensors and chips are used to measure status and communicate about a product's need for repair or opportunities for upgrading; they also enable personalization through, for example, inbuilt thin screens that allow the appearance of many products to be altered. These components are difficult and at times impossible to remove but themselves contain valuable metals and minerals.

Producers have been able to meet their societal and legal obligations through product durability and remanufacturing, and the result has been a significant decline in raw material consumption and flows to "waste." However this also means that the waste management and recycling sectors role is not radically different than it was in 2018: to manage that which follows production and consumption. The difference is that the volumes being handled are smaller and more complex, and the technical challenges to recycling their materials and energy contents are greater. Both technical and business model innovation has been necessary for the sector's survival and profitability in this role. Revenue streams to the sector are multiple – some new, and some familiar but in new combinations.

Increased lifespans for products also means that "sins of the past" live on in recirculating products. Restrictions on toxicity in materials have increased steadily over the years, meaning that at any given point some products in circulation are not living up to new requirements, and must be destroyed when they are worn out. Those who dispose of products and materials must pay a charge for decontamination, which usually happens via incineration. This, in turn, requires sorting of waste streams according to chemical contents.

Plastic, fiber and composite material have become more durable and complex but more difficult to recycle, with more types of plastic being used in more combinations for optimized functionality. Across multiple product categories material recycling has not meaningfully increased, and waste management for these goods is based primarily on thermal and chemical recycling processes.

Waste incineration generates revenue from electricity, heat and cooling generation, operations which are often integrated with complex sorting and separation activities. New thermal treatments are at a smaller scale than earlier generations, and some are highly specialized for the handling of specific fuels and extraction of specific minerals. Other plants are designed for batch incineration, an arrangement well-suited to energy generation, given an energy system that features more distributed resources and places high value on production flexibility.

With industrial technology and export markets continuing to drive demand, an increasing part of the waste management sector's revenues come from extraction of metals. A major source is electronics – a category that now also includes separated parts from most consumer goods and clothes. Chemical, thermal, and biological processes are used to isolate metals, and metals and mineral nutrients are recycled from sludge for use in agriculture and industry.

The need to continue incinerating certain material streams creates pressure to develop more bio-based materials. The cost of fossil emissions from incineration has been pressed upstream, via

taxes and charges, towards producers, creating an incentive for more bio-based content. Fossil content lives on in durable structures – primarily buildings and other infrastructure.

This means that by 2045 carbon capture and sequestration/utilization has been implemented at a few of the larger plants where waste is incinerated. The economics of these plants is supported by innovative incentives. Fossil content is paid for by producers, with corresponding subsidies to CCS. Even the capture of biogenic emissions is given a value through certificates for “negative emissions.”

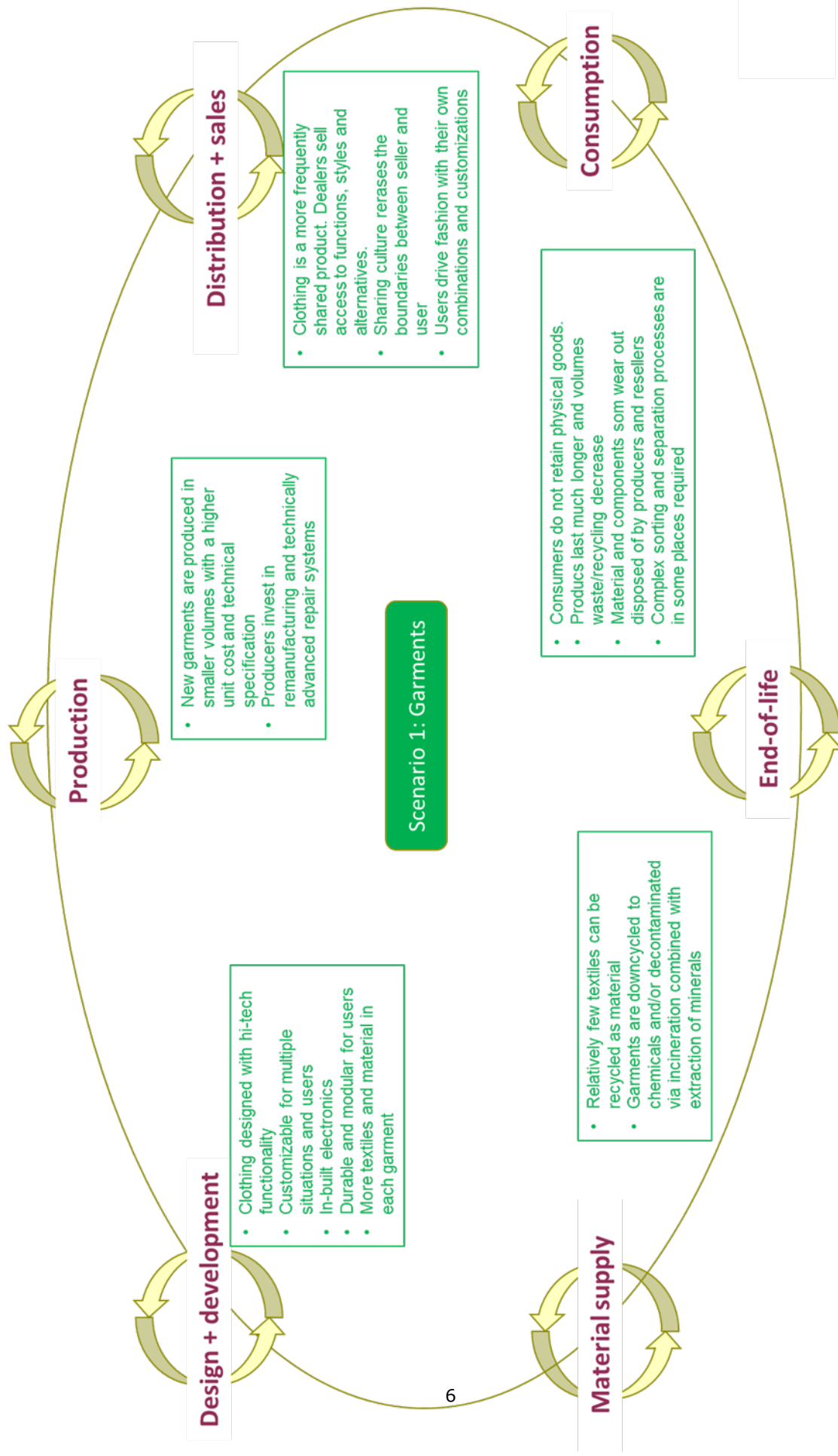


Figure 1: Garments in the value circle, Scenario 1 Sustainable Consumption

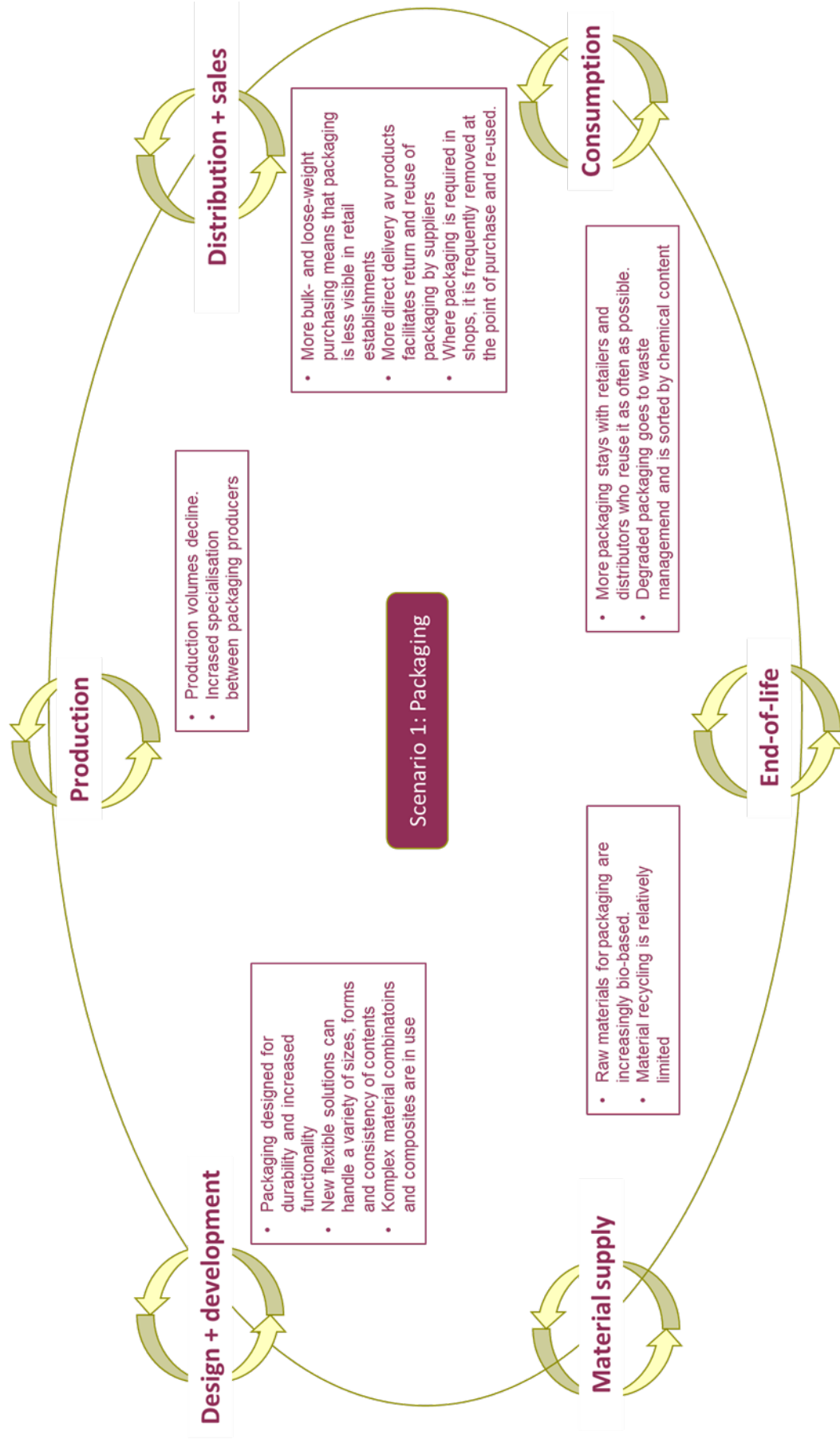


Figure 2: Packaging in the value circle, Scenario 1 Sustainable Consumption

SCENARIO 2: DEEP RECYCLING

Distribution, sales, and consumption patterns are broadly similar to 2018. Material recycling, however, has reached very high levels. Recycling and material supply to industry have been integrated in symbiotic and otherwise linked socio-technical systems, and the technical and economic conditions for energy recovery are defined in large part by arrangements for the provision of secondary raw materials. Incineration is an integrated part of these systems and a range of different business models for waste incinerators.

In 2045 Sweden is in the midst of a major transition: from the linear economy that dominated the world after the industrial revolution, towards a circular economy, where the value in the earth's resources is increasingly preserved within the economy. By this point the transition has come so far, and has required so little of consumers and citizens, that most Swedes do not notice the changes anymore. In less than two generations' time, Sweden has completely altered its socio-technical systems in such a way that design, production, and material handling all serve a model of deep recycling that is integrated throughout the economy.

The transition began in the 2020s, as certain industrial firms and local authorities, in expectation of new and more extensive regulations related to eco-design and producer responsibility, began to share knowledge around what they needed to increase the rate of recycling in their products and materials.

This knowledge sharing had its roots in the research and innovation programs initiated during the previous decade, but gained momentum in commercial contexts. A few large firms, in collaboration with recycling and waste management companies, began to scale up their own activities in the areas of collection, sorting and recycling. New business models built on remanufacturing, material recycling, and symbiosis showed themselves to be economically viable, and the initiatives were positively received by customers and society more broadly. These good examples became inspirations for other companies as well as for politicians and authorities. Between 2025-2030 producer responsibilities were tightened across multiple sectors, and by 2035 most manufacturing firms had taken ownership over large parts of the material flows associated with their products.

The key success factor in the development of circular processes and business models was access to knowledge, technology and infrastructure that had traditionally been external to companies' own value chains. To reconfigure production processes towards secondary raw materials, companies needed access to material streams whose contents and properties they could trust; technology for sorting, upgrading, processing and decontamination, and capacity to handle residuals.

Collaboration with waste management and recycling companies led to an ever-increasing integration of previously separate technical systems for these functions, with the borders between firms reconfigured according to business relations instead of according to placement and usage of physical assets. In many cases recycling and waste handling processes were moved to physical proximity of production facilities; in other cases traditional production processes such as pre-treatment were moved to locations where secondary raw materials arose, often coupled to waste management activities. These developments are facilitated by a broad implementation of Internet-of-Things (IoT) solutions, which made components and even materials traceable and gave an ever more detailed picture of the properties of different streams to and from producers.

Soon the integration of recycling/waste management with production spread to the design stage. Companies realized that meaningful competitive advantages could be created through a

more thorough design-for-recycling, since they would allow more and better secondary raw materials could be secured at lower costs. Producer responsibilities were no longer driven by regulatory requirements but by economics and competitive strategy.

During the 2030s most final products – both industrial goods and consumer goods – are designed for simple recycling through disassembly, material separation and even chemical processes. These products did not generally live longer lives, and were not customized for re-use or sharing. Instead their modular construction targeted recycling so that components, layers, and materials could easily be separated, up- and downcycled as required, and they are recycled in large-scale flows.

Plastics and textiles are used in fewer combinations, and where material is combined in soft constructions, the layers are easy to separate. Complex composite materials are primarily used in expensive technical products with longer life spans (e.g. in industrial applications), and their presence in consumer goods is limited. On the other hand bio-based plastics are increasingly common. Bio-based plastics grow rapidly in consumer electronics, in part because incineration of some plastic remains difficult to avoid as part of rare metals recovery. Bio-based design and materials for electronics becomes an export success as global manufacturers adopt the Swedish approach.

During the transition producers retained their existing sales- and distribution logic, and continued to introduce new products to the market frequently. The flow of material through the Swedish economy remained high, but demand for virgin raw materials – except for bio-based ones – declined rapidly from 2035.

Waste management and recycling firms became suppliers of input materials – sometimes in symbiotic cluster arrangements but often in a broader, cross-sectoral role. The importance of knowledge about a range of material streams' properties and the ability to connect multiple value chains drove rapid growth in this sector, and industrial engineering educations became increasingly oriented around these competences.

This knowledge, complemented by a rapid growth in digital brokerage and marketplaces, was the foundation of a large, dynamic and cross-sectoral trade in secondary raw materials by 2040. Even those smaller firms that could not secure control over their own material flows gained access to affordable, high-quality recycled materials and components.

For households and consumers this transition was almost invisible. The sharing of products remained a marginal phenomenon, and servitization/functionalization grew almost exclusively within business-to-business provision of heavy, durable goods and through large-scale procurement. More effective recycling was achieved without any stricter requirements at the household level, thanks to design for sorting, disassembly and recycling.

Incineration of waste occurs first and foremost as an integrated part of large-scale material supply. Various components, materials and chemicals are separated at various stages of the recycling process in accordance with processing or upgrading needs; incineration plants operate as the final funnel for extraction of valuable contents. Business models for waste incineration vary significantly from case to case, depending on which material supply the incineration is connected to. In some cases, waste incinerators earn most of their income from chemicals, electricity and heat; others are more focused on energy; and others are specialized in the extraction of minerals and metals from ashes.

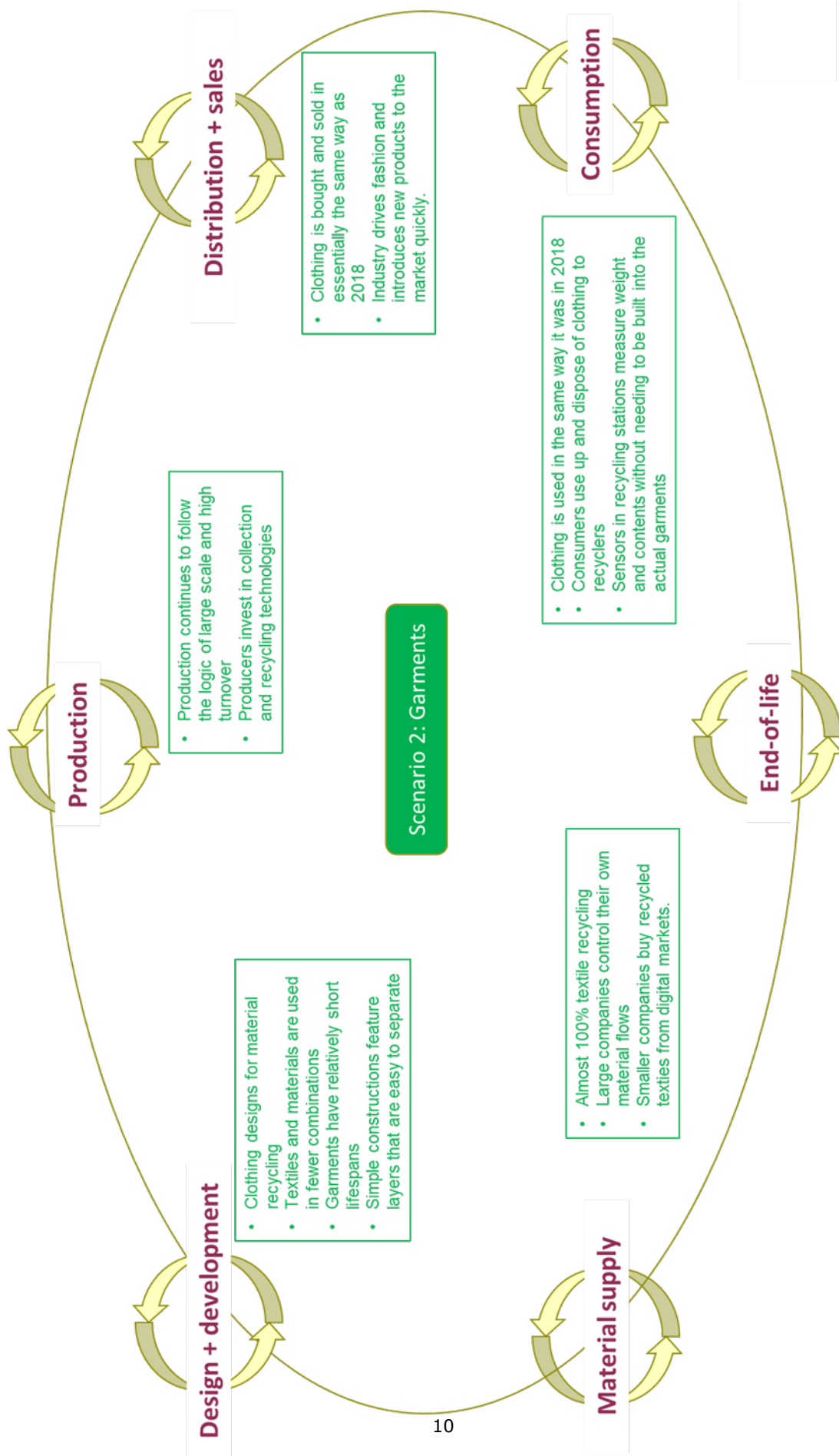


Figure 3: Garments in the "value circle", Scenario 2 Deep Recycling

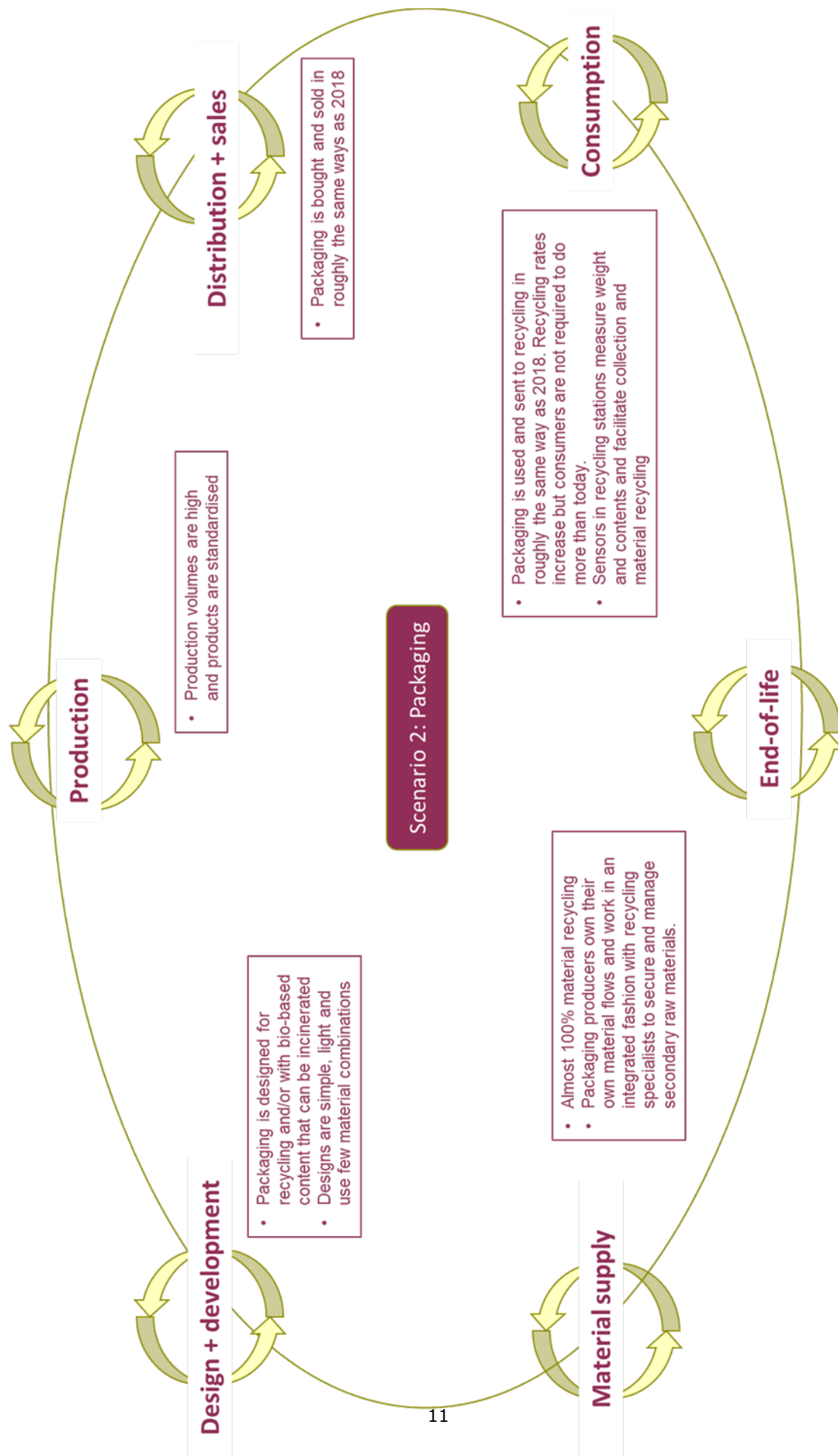


Figure 4: Packaging in the "value circle", Scenario 2 Deep Recycling

Conclusions from the scenario analysis

An important general conclusion from the scenario analysis is that the different driving forces that could support a circular economy are not necessarily synergistic or even complementary. Some trends, strategies, and measures that create opportunities for reuse or remanufacturing can create difficulties for material recycling and even chemical and energy recovery. Conversely, a system for comprehensive material recycling and secondary raw material supply can be developed in ways that reinforce today's consumption patterns and thus hinder new circular solutions. Sector- and even material-specific strategies, roadmaps, and assessments that take specific technical and business realities into account are needed.

These plans and assessments will be of interest to the waste incineration sector to the extent that they can provide insight into the different streams that may require incineration in the future. Both the scenarios above imply a significant need for innovation in the waste incineration sector. To remain relevant and continue to create value in a circular economy the sector will have to innovate in energy technologies, system design and integration, and business models, while also contributing to policy- and strategy development that brings clarity and generates momentum for these innovations.

Even highly circular economies will need waste incineration. But incineration will have to meet new needs and create new value, for example through mineral and metal extraction or through symbiotic production- and supply systems. It will likely have to be more integrated with other sectors and technical systems, both in physical terms and through knowledge sharing.

The remaining sections of this report discuss the innovations that project stakeholders, in light of the scenario analysis, believe that the incineration sector should prioritize.

Priority areas for innovation and action plans

Project stakeholders have identified, based on the scenario analysis, four overarching areas where innovation should be prioritized for waste incineration meet the requirements of a future circular economy:

Value from ashes. In both scenarios, valorization of ashes was viewed as an important part of the sector's future economics. To achieve this innovation is needed around:

- Specialization of plants for custom ashes
- Batch incineration for resource extraction
- Extraction of phosphorous from sewage sludge
- Market development and brokerage
- Resource tracability for ash landfilling

Actions plans have been developed for both phosphorous extraction and market development, and are presented in sections 3.1 and 3.2 below.

Energy recovery in industrial symbiosis. This issue was particularly important in Scenario 2, 'Deep Recycling,' where waste incineration becomes an integrated part of material supply and production cycles. Important innovations include:

- Analysis of opportunities for coordinated collection, material supply and energy recovery
- Prioritization of symbioses in municipal planning, e.g. related to land use

An overall action plan has been developed for this area and is presented in section 3.3.

Difficult waste. This issue was particularly relevant in Scenario 1, 'Sustainable Consumption,' where complex material combinations and plastics/composites make recycling more difficult. Necessary innovations in this area that affect incineration directly or indirectly include:

- Tagging of products for simplified sorting
- Development of more robust boilers
- Collection and sorting of more types of plastic for recycling
- Gasification/chemical recovery from plastics

An action plan for gasification of plastics, including possible connections to/integration with incineration, is presented in section 3.4.

CCS/CCU. Carbon dioxide capture and storage/utilization was mentioned briefly in the scenarios. Even an economy featuring radically changed production and/or consumption patterns is unlikely to generate waste that is completely free of fossil content by 2045. CCS/U is thus a necessary puzzle piece if waste incineration, and Sweden, can achieve the goal of carbon neutrality by that year.

Generally speaking, CCS should be introduced where it provides the most benefit for the required investment. Today it is not obvious that waste incineration is a candidate for first-mover status.

Since capture will always entail an extra cost compared to a plant that releases CO₂, incentives will be required to create a willingness to pay in the value chain.

Today CCS's role in Sweden is uncertain – a situation that may change now that the government has established a commission to look into a national strategy for the technology. Given these uncertainties, the project has not developed an action plan for CCS/U for waste incineration.

ACTION PLAN: EXTRACTING PHOSPHOROUS FROM SEWAGE SLUDGE

The long-term challenge: what do we need to achieve and why?

Phosphorous is a fundamental element for life: a building block of our DNA and key element in energy-rich ATP molecules. Because it cannot be replaced by another element it is also a limiting parameter of food cultivation. Much of the phosphorous used in agriculture is extracted from mine deposits and added to crops via mineral fertilizers. Reserves of mineral phosphorous are finite, and we are nearing the point where easily accessible and high-quality resources are exhausted. In combination with a growing population and economy, this could have serious consequences, and the European Commission has included phosphorous in its list of critical raw materials. Today 90% of mined phosphorous is used in production of food for humans or feed for livestock. On the other hand only a small part of the element is taken up by animal bodies, with the remainder passed in feces and urine. This has inspired much research on the possibility of recycling phosphorous from wastewater.

Today virtually every household in densely populated areas of Sweden (roughly 8,5 million people) is connected to a municipal water treatment plant where phosphorous is separated from water and accumulates in sludge. These areas produce more than 200 000 tons of sludge annually, containing roughly 2 000 tons of phosphorous. The share of this sludge that is used within agriculture has been relatively stable, at about 25%, since the year 2000, despite efforts to improve sludge quality. A societal resistance and uncertainty about health risks are in part to blame. The long-term challenge is to increase the recirculation of phosphorous from sewage sludge; doing so in a way that is socially acceptable probably requires sustainable systems for cost-effective extraction of the mineral from sludge.

During 2018 the Swedish government established a commission to investigate the option of forbidding direct spreading of sludge on cultivated land and requiring the recycling of phosphorous. Experiences from legislation in, e.g., Germany and Switzerland suggest that even under such an arrangement significant time, perhaps 8-10 years, will be required to establish the new systems for recycling.

What should the innovation deliver in 2045?

By 2045 a minimum of 50% of phosphorous in Swedish sewage sludge should be recirculating in society. The solutions contributing to this may vary depending on geographical and infrastructural conditions, and can include direct spreading of sludge; chemical extraction of phosphorous from sludge; or extraction of phosphorous from a mineral-rich ash post-combustion.

The situation today

Technical state-of-the art

The different solutions for recovering phosphorous from sludge are usually grouped in three categories: leaching; non-leaching processes; and thermal processes.

In leaching the sludge is exposed to a leaching solution that causes the phosphorous to liquefy. Leaching of sludge can be done before or after incineration, and can make use of acids, bases or biological systems. Capacity depends on the material, the leaching solution, time and conditions such as temperature. Studies show that acidic leaching is more effective than alkaline, while alkaline methods tend to be more selective. Increases in temperature and tie increase extraction of phosphorous but also other metals, which can be a problem for biological systems.

Non-leaching processes include the use of chemicals that cause precipitation, added directly to the sludge, causing the phosphorous to separate in solid form. These technologies are only applicable to biological water-treatment systems, which today represent only a few Swedish plants.

Thermal solutions involve the incineration of sludge followed by the heating of ash in the presence of chlorides. The metals transition to chloride forms and separate as gases.

The major barrier to the implementation of all of these systems in Sweden today is that the extracted phosphorous is more expensive than mined phosphorous. This gap could be closed by the aforementioned policy framework, should it be adopted.

Ongoing research and development

A great deal of research shows that both wastewater and sludge have positive effects on vegetation. Unfortunately a number of studies also show that heavy metals in sewage sludge can be available for uptake by plants. Concerns about organic contaminants have also been raised, especially related to pharmaceutical traces detected in wastewater and sludge. These could potentially give rise to metabolites that are difficult to analyze and whose effects are uncertain.

A number of studies have also looked at separation of metals and phosphorous in post-extraction solutions. A number of techniques involve precipitation at different stages, but there are even solutions based on ion exchange, electrochemistry, etc. Even if these prove technically viable, they will involve additional costs for water treatment.

A number of projects and initiatives are currently ongoing in Sweden. These cover inter alia:

- Selective/controlled incineration to produce ashes that can be spread directly on cultivated land. (Högskolan i Borås)
- Biochar from sewage sludge (Bla Ekobalans Fenix)
- Extraction from ash (Fortum Waste Solutions, Easy Mining)
- Test bed for phosphorous recycling (RISE)

Key development needs

Significant knowledge exists about the general properties of sewage sludge, but since its content is heavily dependent on local conditions a database cataloging variation would be valuable, particularly in the design of partly local solutions. A parameter of special importance is which chemical form the phosphorous takes in the sludge, as this has implications for leaching.

Another important issue is drying and handling of the different sludge fractions. Drying requirements vary depending on the technology used for recovery. A discussion at a regional level could provide guidance on possible approaches.

General technology development to achieve cost effective recovery from ashes is also needed. Here a test bed or similar arena would be valuable for developing new solutions and testing the performance of existing technologies.

The possibility of recycling other nutrients in connection with phosphorous recovery needs to be investigated in support of a more circular economy.

Which physical form(s) are appropriate for recycled phosphorous is another issue that needs to be handled, as the shape, size, consistency etc. is tied to technology and product development.

Policy development will be crucial to recycling of phosphorous and other elements.

Estimated time to commercialization/implementation

While the transition itself will take time, discussions about future sludge handling etc. need to begin today. As there are a handful of countries at the leading edge of the transition, guidelines for recovery and recirculation levels etc. should be possible to develop within the coming four years.

Decisions about and construction of dryers may take the most time. Discussions about localization, financing, etc. should begin today.

Implementation and commercialization will probably proceed at different paces in different parts of Sweden.

Key measures to promote development

1-2 years:

- a) Creation of reference groups (water treatment companies, municipalities etc.)
- b) Construction of a database of sludge contents that allows, for example, multicriteria analysis to determine drivers of sludge contents.
- c) Evaluation of options for localization of drying plants
- d) Finalization of regulations around sludge handling and phosphorous recirculation.
- e) Ongoing analysis of experiences from first-mover countries

2-5 years:

- a) Investigate phosphorous formation in sludge
- b) Investigate possibilities for simultaneous recovery of other nutrients or valuable minerals
- c) Development/improvement of cost-effective methods for phosphorous and other nutrient/mineral recovery
- d) Quality assurance methods and guarantees of origin for phosphorous
- e) Construct pilot plants

Key actors and their roles

Business

- Technology developers
- Fertilizer manufacturers – which forms are interesting for their processes? What metal levels are acceptable?
- Waste and recycling companies
- Water treatment companies – Can water/sludge handling be altered to make the recovery process simpler in the future?
- Energy companies – incineration
- Transport and logistics – especially important if a network of local/semi-local/central drying/incineration plants is to be designed

Institutes and universities can contribute knowledge, especially related to specific reactions in incineration/leaching.

Public sector

- Municipalities should investigate whether changes in existing processes are needed
- Regions can promote/create conditions for collaboration between municipalities
- Agencies should acknowledge the priority of this issue and set requirements

ACTION PLAN: DEVELOPING A MARKET FOR ASHES FROM ENERGY GENERATION

The long-term challenge: what do we need to achieve and why?

Around 1,7 million tons of ash is produced each year as a by-product of energy generation in Sweden. Most of this ash is classified as non-hazardous waste, and thus could replace, for example, natural gravel as a construction material.

Bottom ash from waste incineration has long been used as a material for final coverage for landfills or for securing leached wastewater. Such projects are coming to their end and new uses are few, which risks a situation where more and more incineration ash must itself be landfilled.

An important challenge is thus to create conditions for utilization of ashes outside of landfill and wastewater management. This will require technical solutions but also environmental analysis, logistics, trust and credibility, allocation of responsibility, and new business models.

Logistical challenges include development of large-scale storage and the capacity to extract and deliver large volumes on demand. Delivering the correct ash where it is needed while increasing overall resource-efficiency and sustainability will also be a challenge. End-users of ashes will need support to secure environmental permits. The properties of the ashes themselves may need development if they are to be seen as attractive and environmentally friendly construction materials.

What should the innovation deliver in 2045?

By 2045 the majority of ashes from the Swedish energy system should be acceptable for use as construction material, for example in large-scale efforts like road construction. This acceptability should be reflected in a well-established market for ashes.

The situation today

Technical state-of-the art

Slag-sorting technologies can already separate metals, glass and other contaminants from slag. The KEZO waste incineration plant in Switzerland has a system in place that sorts slag from both KEZO and surrounding facilities. All of these plants have converted to dry ash output to increase the yield of metals from the ashes. The sorting facility prioritizes separation of metals down to ash fractions of 0,2 mm; glass is also removed from larger fractions. The process is under continuous development by the research foundation connected to the facility.

In Kolding, Denmark Meldgaard operates a modern, stationary facility that separates metals from the ashes from a waste-fired combined heat and power plant. The sorted slag is sold for use in building- and roadworks where it replaces materials such as sand or crushed stone. This has reduced costs for the construction projects as well as the need for raw material extraction.

In Copenhagen Afatek processes ashes from a number of Danish waste incinerators. They are working to improve both the metal yield and the overall quality of the aggregate.

In Sweden Sysav is currently investing in a new sorting facility that will more effectively separate metals. A number of entrepreneurs are also working on batch sorting of ashes for energy generators.

EON is building the first boiler in Sweden with dry ash output; slag sorting will be done by RagnSells. The impact of dry output on the usability of the mineral fraction is not yet clear.

There has been a suspicion that metal extraction worsens the slag's properties as a road- and building construction material. The project [Användning och modifiering av metallseparerat slaggrus](#) has investigated this issue without finding any indication of problems for construction uses.

Askungen Vital is a family firm that provides bio-based ashes from producers to land owners. They have equipment for both processing and spreading of ashes as well as environmental analysis capacity. They also handle permitting and other documentation such as mapping of spreading areas.

Ongoing research and development

- "Recycling of ashes from energy facilities, Handbook 2010:1" (Naturvårdsverket) is being revised with input from the industry.
- Within Waste Sweden an ongoing project is investigating gasification of fly ash with the purpose of creating inert materials that could be approved for use in construction.
- A commission within Waste Sweden is looking at responsibility issues including possible handing of returns.
- Various ongoing initiatives are building knowledge about the chemical composition of ashes and methods for classification according to waste handling regulations.
- A number of initiatives are looking into recycling of salts and metals from fly ash. A full-scale implementation in Denmark is being built with support from EU-Life+.
- A project about Future waste fuels within the Re:Source program is undertaking a state of the art analysis including options for upstream work for relevant to ashes.

Key development needs

Knowledge about leaching and construction properties exists for many ash types but not all. A number of test sites/surfaces have been built over the years that allow for long-term follow-up of environmental and durability aspects.

Unlike Denmark, for example, Sweden does not have clear rules about material that can be used to contain leachate. Applications for use of ashes in these context have been few; a collaboration between the industry and regulating authorities to address this gap would be desirable.

A side effect of this lack of clarity is that little work has been done in Sweden to improve environmental properties of ashes. More clarity is needed about what performance this development should target.

Both emerging and existing knowledge needs to be more effectively shared throughout the value chain, including plant owners, construction companies, local authorities, building and infrastructure owners, and consultants. Aside from material properties, information about lead time for permitting would be valuable for project planners.

There may exist a business case for "ash brokers" or other material providers who can guarantee quality and volumes to construction projects. In general new business models may be needed to create added value from more actors than just incinerators.

Further upstream, knowledge is needed about what waste streams contain the most problematic substances from an environmental perspective so that incinerators could make active choices with impacts on ash usability in mind.

Test and demonstration of treatment is necessary, but the broader development of the market will likely require experimentation and learning from commercial experiments and entrepreneurial efforts.

Estimated time to commercialization/implementation

Full implementation may require some time but development needs to get underway to avoid large amounts of slag being landfilled in the coming years. Given the development time for treatment facilities it may take 6-10 years before marketplaces for ash are fully developed; to the extent that treatment turns out not to be necessary, market development could move faster.

Key measures to promote development

1-2 years:

- Investigate requirements to REACH-certify ashes
- Investigate what oversight authorities will require (materials, uses) for ashes to be used in construction materials for, e.g., road building.
- Identify niche uses where ashes might provide extra value as a building material.
- Create an information repository for projects where ashes have been used outside of the landfilling context and follow up their environmental performance and durability.
- Establish a common, large-scale storage space for bottom ash for later use. Such a store could be administrated by one or more "ash brokers" and could also take in other materials such as pit rubble, stone, etc.
- Offer support to construction companies and other actors in securing permits to use ash as a building material.

2-5 years:

- Determine which treatment of ashes is needed based on the points above.
- Identify appropriate use cases for different ashes depending on quality requirements.
- Sound out interest for a marketplace/brokerage services that match ash producers with potential purchasers. Investigate relevant examples of such market-making services throughout Europe.
- Investigate the economics and desirability of a stationary facility that could take in and process slag fractions into usable materials, along the lines of the Meldgaard facility in Denmark. A possible combination with glassification of fly ash could be something approaching a one-stop shop.

ACTION PLAN: ENERGY RECOVERY WITHIN INDUSTRIAL SYMBIOSIS (IS)

The long-term challenge: what do we need to achieve and why?

The future circular economy will require multiple ways of generating value from different waste streams. A stable and competitive energy supply will still be important, and energy flows of energy – including embedded in waste -- will have to be managed in new ways. For example, material recycling processes may generate residues that are contaminated or difficult to monetize, but which have energy content. Framework conditions such as policy, infrastructure, and knowledge and awareness will determine the acceptability of energy recovery in the long-term.

What should the innovation deliver in 2045?

Recovery of energy from waste should:

- Be seen as an opportunity or enabler for Industrial Symbiosis (IS) and not as a barrier
- Improve the competitiveness of other industrial activities
- Maximize value through cascade-utilization of energy
- Act as a fulcrum for increased material and feedstock recycling

The situation today

Technical state-of-the-art

Many examples of IS are not based on unique technical functions but rather on sharing of resources, material- and energy flows. About 20 IS structures have been identified in Sweden today, many with a connection to energy recover from waste (for example in Norrköping, Helsingborg, Linköping and Lidköping). ¹

Ongoing research and development

The European Union sees IS as one of many important approaches to the growth of the circular (bio)economy. Many of the reported examples have arisen directly between involved parties, though there have also been cases where local and regional authorities played supporting roles. It is clear that physical conditions, societal processes and policies all play important roles in IS. ²

The project "Shared energy is doubled energy" provides an example where local actors attempted to identify opportunities for symbiosis early in municipal planning processes.³ The project led by the city of Malmö with financial support from Vinnova, also looked at the city's flows of waste, energy and water from a resource perspective.

An effort is also being made to create a national platform for IS in Sweden, whose purpose will partly be to build capacity on a regional basis within the valorization of secondary raw materials through symbiotic arrangements.

¹ Murat Mirata, Peter Carlsson, Steve Harris, Michael Martin, Rickard Fornell, Roman Hackl, Tobias Källqvist, Emma Dalvåg and Sarah Broberg (2018). *International and Swedish state of play in Industrial Symbiosis. A review with proposals to scale up Industrial Symbiosis in Sweden.*

² Ibid.

³ <http://deladenergi.se/> (länk 19 juni -18). Vinnova UDI-projekt som leds av Malmö Stad

Key development needs

Waste-fired CHP are often a part of IS processes, but are also frequently mentioned as a barrier to symbiosis, as they are said to create lock-ins in infrastructure that hinder material recycling. Development is needed at both ends: energy recovery will only be accepted when the energy is based on material that otherwise truly will go to waste. The question of how the energy is then used is also important; in connection with IS processes cascade use is often of interest (e.g. steam→high temperature hot water → low-temperature hot water).

Among other factors limiting the development of IS in Sweden a lack of coordination between national, regional and local levels is significant, as is the need for long-term rules around, for example, standards for recycled materials. Just as existing infrastructure can be limiting, a lack of policy clarity and drawn-out permitting can inhibit the creation of new infrastructure. Here we arguably see parallels with the many planned but cancelled efforts to develop renewable fuel production.⁴

Estimated time to commercialization/implementation

Each IS is unique – not necessarily in terms of its component activities, but in terms of combinations and system design. A cornerstone is relationship development between key actors – this takes time and a willingness to undertake a long-term commitment. Such processes can be strengthened if municipal and regional actors have the necessary knowledge.

Key measures to promote development

- Energy recovery from waste needs to be seen as a facilitator of, and not a hindrance to, IS. Confidence that energy recovery is only based on that which is genuinely not to be used for materials is essential. Remaining fossil content in these fuels should burden the waste generator not the actor recovering the energy.
- Market and business models for high temperature energy (e.g. within district heating) and physical planning for utilization of low temperature energy (e.g. within biological systems, which require significant space).
- Value creation for waste products from energy recovery (gases and solids).

1-2 years:

- Improve knowledge about what is entering plants and what could be diverted to material recycling
- Improve communication with upstream actors about energy vs. material recycling
- Develop business models
- Work on the valorization of waste products (see action plan for development of a market for energy ashes)

⁴ Philip Peck, Grönkvist, S., Hansson, J., Lönnqvist, T. and Voytenko, Y. (2016) *Systemic constraints and drivers for production of forest-derived transport biofuels in Sweden – Part A:Report*. Report No 2016:09A, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

2-5 years:

- Raise IS to the level of strategic planning, including in city planning processes
- Work upstream to continually limit the amount of recyclable material going to energy recovery
- Apply newly developed business models

Key actors and their roles

Harris, et al (2018) note that a success factor for IS is the ability of different actors to collaborate. For energy recovery this requires acceptance of recycled heat.

Cascade usage requires a chain of key actors from operations, for example an actor with a drying requirement able to provide steam for another actor's hydroponic facilities. For these activities to be connected they must lie near each other, which can be facilitated by local planning.

Business

Technology developers

The infrastructural basis for IS in many cases is nearly ready. Traditional technology development issues are the most relevant: gasification of various substrates, extraction of phosphorous from sludge, increased biomass utilization, more effective heat pumps, etc. New technologies for exploiting waste products from energy recovery (gases, ashes) will be important complements.

Waste management and recycling companies

Recyclers need to work with manufacturers and customize their recycled materials. Standard development may be helpful here.

Manufacturing and process industries

- Manufacturers need to work with recyclers to develop standards that facilitate use of recycled material
- The chemicals industry can support the development of combustion processes that generate both energy and chemical feedstocks.

Institutes and universities should undertake system studies and technology development and identify and communicate opportunities and threats.

Public sector

The public sector needs to create helpful conditions for IS related to policy, legal requirements, infrastructure planning, and communication.

Municipalities should act as facilitators, taking initiative and managing the overarching functions. They should create conditions for related operations to be localized near each other, and act as an institutional anchor for collaboration.

Agencies should manage the relevant permitting processes as effectively as possible.

ACTION PLAN: GASIFICATION OF DIFFICULT WASTE

This action plan concerns waste that is difficult to incinerate or gasify for energy recover in traditional facilities. The waste may have different origins, but a significant amount is today rejected from mechanical sorting processes in the recycling industry. One reason this waste tends to be difficult to handle is the tendency to cause corrosion damage or other problems with coatings in incineration facilities.

The long-term challenge: what do we need to achieve and why?

Today waste is processed via simple collecting and sorting, with clean and easy-to-handle streams sent to mechanical material recycling. The exceptions are vehicles and electronic waste, for which mechanical recycling is more advanced. Today's different waste management systems are constructed to meet competition for cheap raw materials, and to meet politically-determined producer responsibilities for recycling.

Acceptance of waste as a potential resource is on the rise, particularly among manufacturers who increasingly send reuse waste from production processes, or send it to raw material suppliers for upgrading.

A difficulty for many waste streams is that many products contain chemical additives related to coloring, surface structure, durability, fire safety, etc. Today's material recycling systems generally struggle to separate these additives, which increases the risk that recycled materials can contain contaminants.

In a future circular economy, even difficult waste will need to be seen as a resource. This will likely mean that the waste going to incineration will look different – a larger portion will be waste that today is considered "difficult." Today's technologies for energy recovery will not be the obvious choice in the future: tomorrow's incineration facilities will have to be more robust.

Questions worth considering include:

- Can energy recover from difficult waste be combined with material recycling by way of a gasification step?
- Can difficult waste be recycled as materials with new, more efficient technology?
- Will multiple, different material recycling systems for difficult waste be necessary? How can such systems work together?
- How should today's energy recovery facilities be developed to be able to handle a larger share of difficult waste?

In this action plan the focus is on the potential of gasification technology as a facilitator of material recycling. Gasification offers a path to chemical recycling of difficult waste such as contaminated plastics, potentially generating an energy gas that can be combusted for electricity and heat.

The situation today

Today most difficult waste – even fractions that could be recycled mechanically – goes to incineration.

Technical state-of-the-art

Gasification of biomass exists today. The GoBiGas plant in Gothenburg (20MW), demonstrated gasification wood chips and pellets to syngas, later converting to methane to be fed into the natural gas distribution network. Commercial-scale gasification of waste exists, for example, in Lathi, Finland. These plants generate gas that is later used as fuel for energy generation. An

alternative approach has been developed in Canada, gasifying household waste to produce ethanol. During 2018 a consortium consisting of Air Liquide, AkzoNobel Specialty Chemicals, Enerkem and the Port of Rotterdam signed an agreement to develop and provide initial financing for a similar facility in Rotterdam.

Ongoing research and development

Chalmers Institute of Technology has a demo plant (2-4MW) for gasification connected to their circulating fluidized bed combustion furnace. This facility drove the development that was demonstrated further by GoBiGas (now been mothballed for economic reasons). But Chalmers continues to research waste gasification: both PE-granules from Borealis (a production waste) and plastic waste pellets from scrap upgrading by Stena Recycling have been gasified with promising results. This research has show that the fuel contents significantly affect the yield of energy gas; the more homogenous the input, the better the yield. Ongoing tests with plastic waste are planned for winter 2018-2019.

RISE ETC in Piteå has also attempted to gasify waste. In their pilot plant (10-20MW) they have performed high-temperature gasification of Stena's waste pellets, demonstrating that dioxin emissions can be reduced relative to incineration. A continuation of the project to evaluate the product gas yield has been approved within the Re:Source program.

The new firm Bioshare⁵ is developing a gasifier that can be mounted in a fluidized incineration furnace, so that produced gas can be used as a fuel that replaces fossil fuel in plants that cannot take in solid waste. The gas can also be upgraded to syngas or chemical feedstock.

The chemical companies in Stenungsund have developed a roadmap for fossil-free operations, including the goal of having a recycling-based refinery in operation, by 2030. The refinery would convert waste, by pyrolysis and/or gasification, to a chemical feedstock. The Chemical- and Materials Cluster of West Sweden is working with a number of projects and applications for research and development related to waste gasification.

Key development needs

Biomass gasification is relatively well understood but more knowledge is needed about how different materials perform in a gasification unit, which technology is appropriate and which product arises depending on inputs. Technologies for cleaning the output gases will also be needed, and their development depends on the answers to the preceding questions.

The difficult waste of the future will include halogens, and the effects of halogens on gasification equipment, cleaning equipment, and product gases will need to be investigated. Research into combinations of technologies and processes will be needed to ensure maximized energy recovery. In this perspective the fractions that may not be suitable for material recycling or gasification, which will need to be incinerated, must also be considered. They will likely create new requirements for incineration facilities.

Estimated time to commercialization/implementation

While gasification technology exists today, it is unclear which technologies suit which waste streams and how much variation within the input streams the different options can handle. Which products are most attractive will be determined by market development, which in turn is

⁵ www.bioshare.se

affected by different incentives. Today there is no economic support for bio-based or chemically recycled products; subsidy support remains exclusively for bioenergy. Today, incineration of difficult waste is clearly less expensive than material and chemical recycling options. A commercial facility for chemical recycling is likely many years away – though the chemical companies' goal of 2030 may be achievable.

Key measures to promote development

1-2 years:

- Build knowledge around gasification of different waste streams and cleaning of the generated gases
- Suggest policies that incentivize use of bio-based or recycled products and chemicals
- Investigate how plants can be connected to production via industrial symbiosis (broadly defined)

2-5 years:

- Pilot plants in operation for certain fractions
- Incentives in place that ensure long-term and stable investment conditions
- Continued technology development based on learnings from pilot plants

Conclusions from the action plans

Society is changing and large-scale transitions in a number of areas have already begun. These changes will impact waste management, and incinerators need to be prepared to adjust and find their role in the emerging context. The sector will need to expand its horizons and beyond the problems it has already identified and is dealing with today. Working with longer time horizons and greater uncertainty will be challenging.

The method used in this project has proven helpful, though difficulties in maintaining the long-term perspective proved unavoidable. The resulting action plans are thus a mixture of plans for meeting today's challenges and addressing the long-term issues. Of course both are necessary for the incineration sector to successfully play its role.

The action plans developed address only a selection of the issues discussed within the project and the scenarios. The selection was driven primarily by the stakeholders themselves and is not meant to imply that other challenges are not important.

The waste incineration sector now must move forward and implement the action plans. The companies themselves can take the lead on some of the actions identified; others will require coordination and collaboration with others. The sector will need to take initiative on these collaborations.

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Further Information

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