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Learning effects in roadmaps

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Learning effects in roadmaps

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Summary

Roadmaps provide an outlook on the future and estimate how specific plans and measures can contribute to reaching certain targets in the future. However, technologies are not static, and specifically, new technologies are still expected to have improved performance over time. This effect is known as a technological learning effect, where a repeated action leads to an improved performance, which can also lead to lower costs and environmental impacts. The scientific literature on the implementation and calculation of learning effects and learning curves is broad. However, not much is known about how learning effects are included in grey literature such as roadmaps.

This study reviewed how ten recent roadmaps in the context of sustainability included learning effects. Specific measures were categorized according to (i) two kinds of scenarios, being a current policy scenario or a scenario aiming at improvements; (ii) seven types of changes, i.e. a demand in-/decrease, a demand-shift, an input decrease, an input-shift, an output decrease, a decrease in the upstream environmental impact of the inputs and a decrease in the downstream environmental impact of the outputs; (iii) two types of effects, being a direct and an indirect effect; (iv) three types of technologies, being mature technologies, emerging technologies, and new technologies; and (v) three types of estimations, being an expert estimate of a value, an expert estimate of a change and an extrapolation of historical data. In addition, five recommendations, based on an earlier review of learning effects in the scientific literature, were assessed for these ten roadmaps.

The results showed that where scientific publications often consider learning effects on the environmental or economic product level, the roadmaps focussed more on improvements in the technical component level. Historical data was only used by one roadmap. The transition towards renewable energy was included as an indirect event in the background by almost all roadmaps. However, the global warming impact of this future energy mix was assumed to be zero, which disregards the impact of material extraction and waste management required for renewable energy. It is therefore recommended to also incorporate the impact of the material footprint of the renewable energy transition when discussing future scenarios. All the included measures can be related to the circular economy strategies, although the targets of all roadmaps primarily focus on minimizing climate impact. This illustrates how circular economy strategies act as a means to an end, although this is not acknowledged by the roadmaps themselves. A roadmap with a circular economy as a target should therefore keep in mind that a circular economy is not a goal in itself but is a strategy to achieve a more sustainable society.

Samenvatting

Roadmaps bevatten een vooruitblik op de toekomst en proberen in te schatten hoe bepaalde maatregelen bij kunnen dragen aan het behalen van toekomstige doelstellingen. Technologieën zijn echter niet statisch en verbeteren doorheen de tijd. Dit effect staat bekend als een technologisch leereffect, waarbij een herhaalde uitvoering van een bepaald proces leidt tot een verbeterde prestatie, wat ook de economische kosten en milieu-impacten van dit proces kan verlagen. Er bestaat reeds een uitgebreide wetenschappelijke literatuur rond de berekening en toepassing van leereffecten en leercurves. Over het gebruik van deze leereffecten in 'grijze literatuur' zoals roadmaps, is echter nog maar weinig bekend.

In deze studie werd een review uitgevoerd van tien recente roadmaps in een duurzaamheidscontext om het gebruik van leereffecten te analyseren. Specifieke maatregelen werden onderverdeeld in verschillende categorieën op basis van (i) twee soorten scenario's, een scenario op basis van het huidige beleid of een scenario gericht op veranderingen; (ii) zeven soorten veranderingen, namelijk een stijging of daling in de vraag naar een bepaald product of dienst, een vraagshift naar een alternatief product of dienst, een daling in inputs, een verandering in inputs, een daling in outputs, een daling in de voorgaande milieu-impact van de inputs of een daling in de verdere milieu-impact van de outputs; (iii) twee soorten effecten, zijnde een direct of indirect effect; (iv) drie soorten technologieën, zijnde mature, opkomende of nieuwe technologieën en; (v) drie inschattingsmethodes, zijnde een schatting van een bepaalde waarde door een expert, een schatting van een bepaalde veranderingsgraad door een expert of een extrapolatie van historische data. Daarnaast werd de toepassing van vijf aanbevelingen, opgesteld op basis van een vroegere reviewstudie van de wetenschappelijke literatuur, op deze tien roadmaps onderzocht.

De resultaten tonen aan dat waar wetenschappelijke publicaties eerder focussen op leereffecten bij de economische kost of de milieu-impact van het eindproduct, roadmaps leereffecten eerder gebruiken om verbeteringen op het technische component niveau te analyseren. Historische data werd maar gebruikt door één roadmap. De transitie naar hernieuwbare energie werd door bijna alle roadmaps meegenomen als een indirect effect in de achtergrond. Hierbij werd er van uitgegaan dat de bijhorende elektriciteitsmix geen enkele broeikasgasemissies meer zou uitstoten doorheen zijn hele levenscyclus. Op deze manier worden broeikasgasemissies genegeerd die uitgestoten worden bij de extractie van materialen of de verwerking van hernieuwbare energie productietechnologieën in hun afvalfase. Het is daarom aangeraden om ook de impact van de materialenvoetafdruk van de hernieuwbare energietransitie mee in rekening te nemen wanneer toekomstscenario's gebruikt worden. Al de gebruikte maatregelen konden gelinkt worden aan strategieën om een circulaire economie te verwezenlijken, ondanks dat alle roadmaps in de eerste plaats een lagere klimaatimpact als doel voorop stelden. Dit toont aan dat circulaire economiestrategieën een belangrijk middel zijn om bepaalde duurzaamheidsdoelstellingen, zoals een verlaging van het effect op klimaatsverandering, te bewerkstelligen. Desondanks wordt deze rol van de circulaire economie niet uitdrukkelijk besproken door de roadmaps zelf. Een roadmap met een circulaire economie als doel moet daarom rekening houden met het feit dat een circulaire economie geen doel op zich is, maar eerder een manier om een duurzamere samenleving te bereiken.

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List of Abbreviations

FOAK	First-of-a-kind
NOAK	Nth-of-a-kind
MAV	Maximum achievable value
TRL	Technology Readiness Level
CCS	Carbon capture and storage
CCU	Carbon capture and usage

Learning effects in roadmaps

1. Introduction

A process that is being performed for the first time, will not go as fluently as a process that has been performed for thousand times already. Plenty of examples of this learning process are available, from cooking a meal to performing on stage. Examples can also be found on a technological level when a new technology is introduced. In the transition to a circular economy, new technologies are required. These new technologies have a disadvantage compared to mature technologies. As mature technologies have been on the market for some years, there has been already plenty of time for process optimization. New technologies, on the other hand, haven't had this opportunity yet. Therefore, their performance will be worse compared to the performance of mature technologies, while this may turn around when more experience has been gained. It is therefore important to include these effects when comparing new technologies and mature technologies or the performance of new technologies in the future. This concept is also known as a learning effect, where the efficiency of a certain process improves with an increase in experience (Figure 1). A practical application, where estimating the effect of new technologies in the future is key, can be found in roadmaps. Roadmaps aim to provide a look into the future and a prospective assessment of how future changes will influence a specific target. However, no methodological guidance on how to construct these roadmaps was found. As a consequence, little is known about how these roadmaps deal with the concept of technology evolution and learning effects.

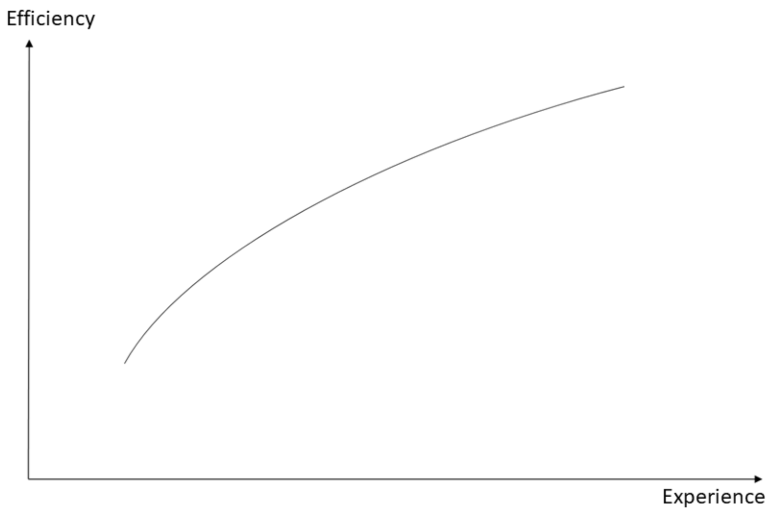


Figure 1. The concept of a learning effect

In this study, a methodological framework on how to include learning effects in prospective technology assessment was applied to the use of learning effects in roadmaps. This was done by means of a systematic review of 10 selected roadmaps. Based on the results, recommendations are formulated aiming to provide methodological guidance on the inclusion of learning effects in roadmaps.

2. Learning effects in prospective technology assessments

2.1. Learning effects

In a prospective technology assessment, the future performance of a technology is being assessed. This future performance can focus on a technological performance, e.g. energy consumption, or can also look into environmental impacts, e.g. the impact on climate change, as well as the economic costs of a technology. An improvement in the technological performance will also influence the environmental impact and the economic costs. A higher energy efficiency decreases both the environmental impacts related to energy consumption as well as costs. A learning effect leads to an improvement of a new technology when it enters the market in a first-of-a-kind (FOAK) application until the technology has become mature in an n-th-of-a-kind (NOAK) application. This learning effect will therefore also lead to a decrease in the economic costs and environmental impact of a technology when evolving from a FOAK to a NOAK application. This concept is illustrated in Figure 2.

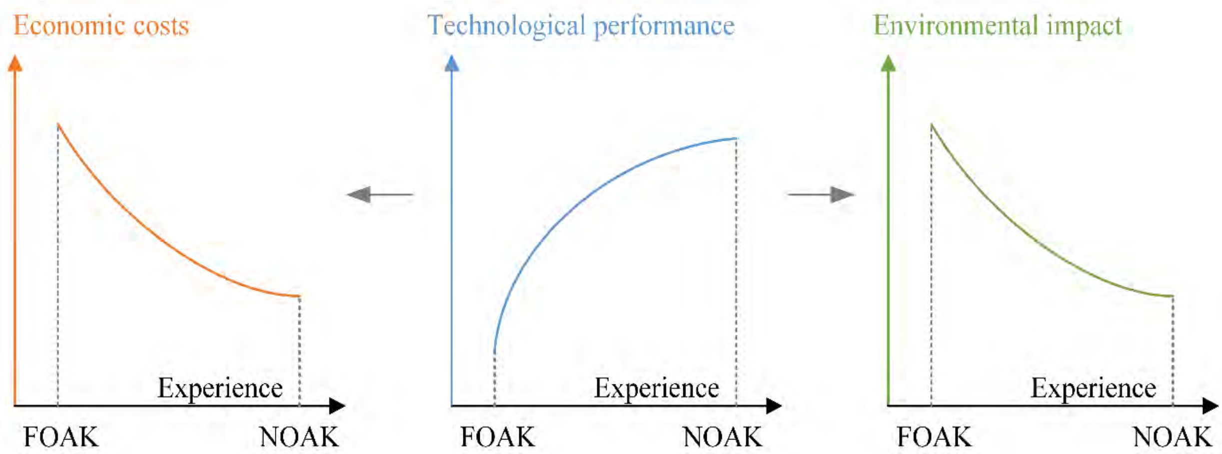


Figure 2. Application of learning effects on technological performance, economic costs, and environmental impact (Thomassen et al., 2020)

A learning effect can occur due to different reasons. When a specific action is repeated over and over again, it is called learning-by-doing. An example of a learning-by-doing effect is changing the diaper of a newborn baby. When the technology itself is improved, it is called learning-by-searching. An example of learning-by-searching is a new sort of solar panel with higher efficiency than the previous model. The performance of producing energy is improved, but not with exactly the same technology. R&D investments are a typical measure to induce a learning-by-searching effect. Besides learning-by-doing and learning-by-searching, other types of learning effects exist as well. These include learning-by-using and learning-by-interaction (Junginger et al., 2010).

2.2. Learning effects in the scientific literature

In a previous study, a review was performed on how learning effects are calculated and/or applied in prospective technology assessments as published in the scientific literature (Thomassen et al., 2020). A major finding of this study was that most applications of learning effects focussed on the cost decrease of solar energy production technologies. An example of such a typical application can be found in Figure 3 (Reichelstein and Sahoo, 2017; Swanson, 2011).

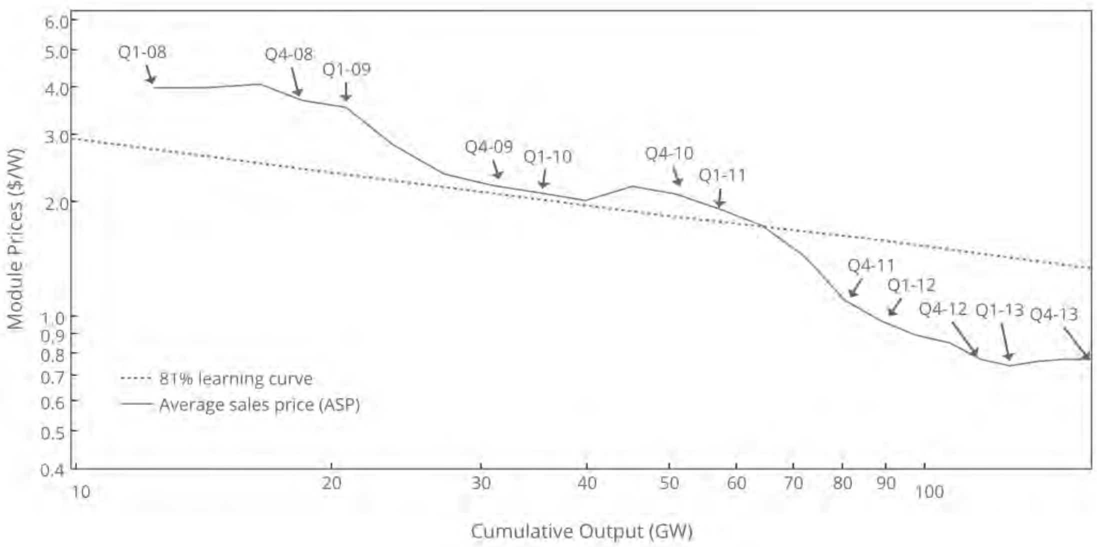


Figure 3. Example of a learning rate application (Reichelstein and Sahoo, 2017; Swanson, 2011)

The 81% learning curve as estimated in this example refers to a progress rate of 81%, or a learning rate of 19%, calculated with the typical learning rate equations:

$$C = C_0(P/P_0)^{-\alpha}$$
$$PR = 2^{-\alpha}$$
$$LR = 1 - PR$$

Where C is the cost per unit, P is the number of units produced, C_0 and P_0 are the initial cost and production units, α is the learning coefficient, PR is the progress rate and LR is the learning rate. The learning rate can be interpreted as the % cost reduction with a doubling of experience.

An overview of the reviewed learning rate, their applications, and the dimensions they covered, being technological, economic, and/or environmental can be found in Figure 4.

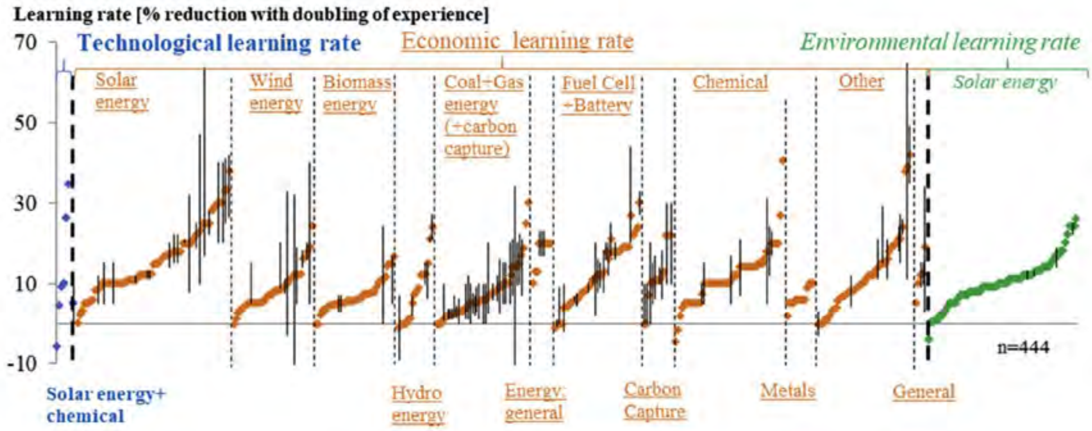


Figure 4. Overview of the reviewed learning rates in Thomassen et al. (2020)

Based on the review study, five recommendations were formulated to include learning effects in prospective technology assessment:

- Combine component and end product level
- Combine technical and economic/environmental dimension
- Combine extrapolated and projected values
- Combine learning-by-doing and learning-by-searching
- Use a tier-based method with quality criteria for the estimation of the learning effect

As illustrated in the example in Figure 3, most studies apply the learning rate to the end product level, for example, the technological performance will reduce by 1% per year or the economic cost of the modules has a progress rate of 81%. However, the real learning effect happens on a component level, when labour costs are reduced due to faster processes or energy impacts are reduced due to higher energy efficiency. However, when only looking at the component level, learning effects might be missed as was discussed in the study by Nemet (2006). It is therefore recommended to combine both perspectives and look both at the component level as well as at the end product level.

The second recommendation is related to the first recommendation. While a lot of the published studies only discussed the learning effect on the economic costs or environmental impact, the effect itself occurs mostly on a technological level. However, similar to the component and end product level, if only the technological level is taken into account, learning effects might be missed. This recommendation therefore also stresses the need for a combined approach. The differences between the component and end product level for the technological, economic, and environmental performance are illustrated in Figure 5. This figure also illustrates the impact of learning effects in the value chain in the background due to future reduction in the carbon intensity of the electricity mix, for example. These effects also need to be incorporated.

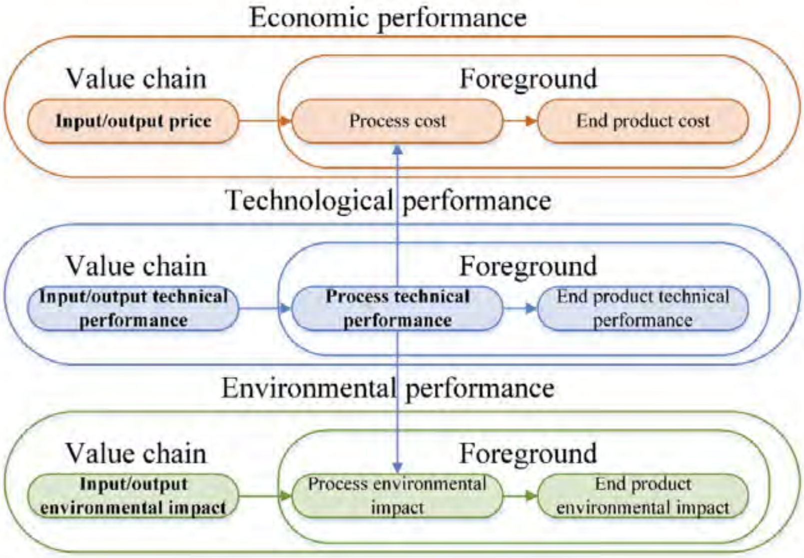


Figure 5. Different places in the value chain where the learning effect may occur (Thomassen et al., 2020)

Where the first two recommendations focus on where the learning effects occur, the third recommendation focuses on how the learning effect is estimated. Two main methods are available, as illustrated in Figure 6. The first method makes use of historical data to extrapolate a learning curve. For this learning curve, the x-axis represents the experience and the y-axis represents the impact under investigation, being the technological performance, economic cost, or environmental impact. The second method uses projected values, often based on expert judgment. The projected values can cover a certain point on the x-axis, for example, the performance in 20 years, but can also cover the maximum achievable value (MAV). For example, energy efficiency can never surpass the value of 100%, and technological limitations will lower this MAV. As both historical data, leading to extrapolations, and expert insights on future values are valuable, it is recommended to make use of both methods if the necessary data is available. Similar to the first two recommendations, this combined approach can lead to differing results which also provides insights on the uncertainty of the estimates based on the chosen method.

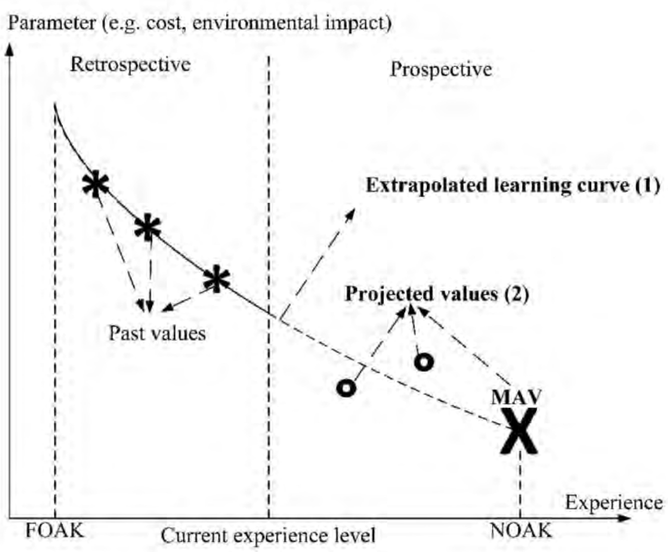


Figure 6. Extrapolating historical data and projected values to estimate the learning effect (Thomassen et al., 2020)

The fourth recommendation focuses on the type of learning effects. As learning effects can occur both due to improvement in the practice (learning-by-doing) and the technology itself (learning-by-doing), it is recommended to take both types into account. This means that learning effects not only cover improvements in existing technologies but also need to take upcoming technologies, which are still in the R&D phase, into account. For technologies in the R&D phase, not only learning effects need to be included, but also development and scale effects still have to be considered. An example of a development effect is the energy consumption when the technology is still in the laboratory phase, where energy consumption is often not optimized. This optimization will happen during a demo or pilot stage phase leading to lower energy consumption for a FOAK application. Scale effects are related to the production scale, where a doubling in production capacity does not automatically lead to a doubling in production costs due to economies-of-scale. A pump with double power does not have to have a double price as well. To differentiate between the different levels of technological maturity, the Technological Readiness Levels (TRL) can be used, where TRL 1-8 relates to a technology still under development and TRL 9 is used to classify a mature technology (Table 1, based on European Commission (2014)). Where learning-by-doing effects focus on FOAK technology applications at TRL9, learning-by-searching effects also cover upcoming technologies in TRL1-8, where also development effects will occur. Scale effects can happen on each TRL as they are dependent on the production capacity and not on the technology maturity.

Table 1. TRL scale (based on European Commission (2014))

TRL	Technological maturity
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

The fifth recommendation provides guidance on how to calculate a learning effect. A tier-based method was constructed, where based on the available data, the most appropriate calculation route was indicated in Figure 7. Quality criteria and rules of thumb were also provided and can be consulted in Thomassen et al. (2020).

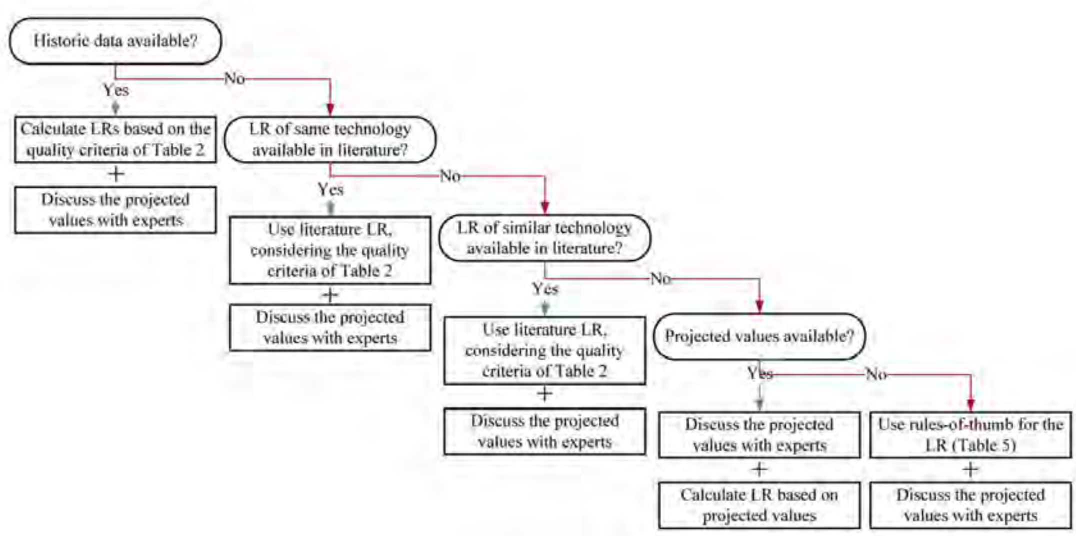


Figure 7. Tier-based method for learning effect estimation (Thomassen et al., 2020)

The inclusion of learning effects in the typical steps of a prospective technology assessment was also discussed as illustrated in Figure 8.

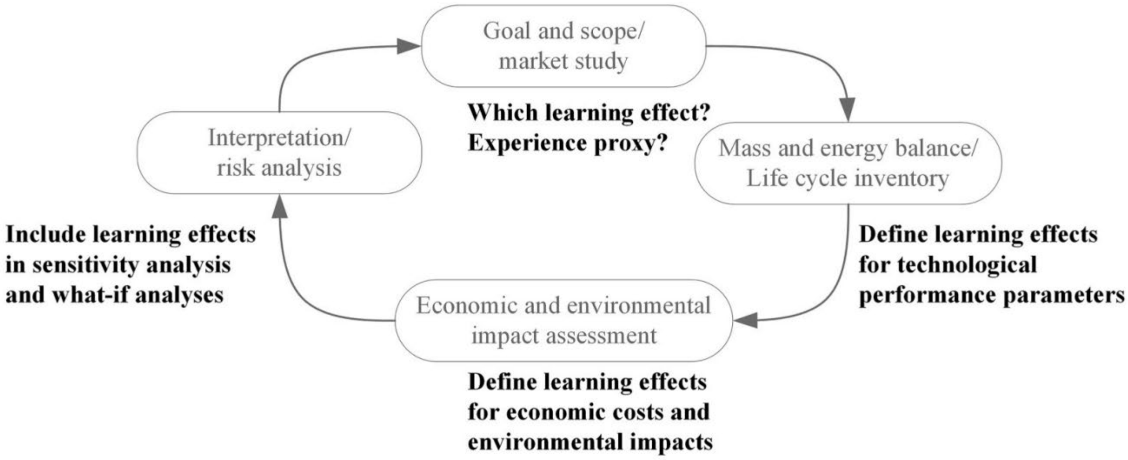


Figure 8. Inclusion of learning effects in the typical steps of prospective technology assessment (Thomassen et al., 2020)

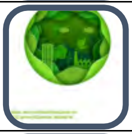
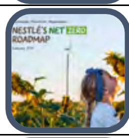
Applications of the inclusion of learning effects can be found on different levels. On a technology level, an application was provided in the study on the end-of-of life phase of silicon-based solar panels, by Thomassen et al. (2022). On a product system level, learning effects were studied in the waste management system of post-consumer plastic packaging in Flanders, from both a retrospective and a prospective perspective (Thomassen et al., under review). A third type of application can be found in roadmaps, where both learning effects on a technology level and a system level are covered. This third type of application will be discussed in the next section.

3. A practical application: learning effects in roadmaps

3.1. Roadmaps

Roadmaps provide guidance on how to reach future targets. They can be both qualitative as well as quantitative. However, as the goal of the study was to assess the inclusion of learning effects, only quantitative roadmaps were included. A selection of ten roadmaps was made, focussing on roadmaps from the period 2018-2021. In addition, also the roadmap of Vlaanderen Circulair was included. Although this roadmap did not provide quantitative measures, it is a key document for the transition to a circular economy in Flanders and is therefore very relevant in the context of the Circular Economy Policy Research Center. As this roadmap also recommends a further quantitative elaboration, the current study can guide this effort. Specific recommendations for the quantification of this roadmap will be provided in Section 5. An overview is proved in Table 2.

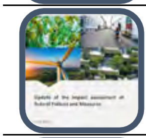
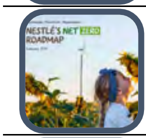
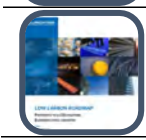
Table 2. Overview of the included roadmaps

Author	Year	Title	Icon
World Economic Forum (2020)	2020	Raising ambitions: A new roadmap for the automotive circular industry	
Deloitte (2020)	2020	Naar een koolstofcirculaire en CO2-arme Vlaamse industrie	
Vlaamse Overheid Departement Omgeving (2018)	2018	Towards a Flemish Industrial Low-carbon Transition Framework	
ICEDD et al. (2021)	2021	Update of the impact assessment of federal policies and measures	
European Commission (2018)	2018	A Clean Planet for all	
Nestlé (2021)	2021	Nestlé's net zero roadmap	
Concawe (2021)	2021	Transition towards low carbon fuels by 2050: Scenario analysis for the European refining sector	

Eurofer (2019)	2019	Low carbon roadmap. Pathways to a CO_2 European steel industry	
Leuven 2030	2019	Roadmap 2025-2035-2050 naar een klimaatneutraal Leuven	
Vlaamse Overheid, Departement Mobiliteit en Openbare Werken	2019	Roadmap voor vermindering van klimaat- en luchtemissies van vrachtvervoer	
Vlaanderen Circulair	2022	Toekomstbeelden voor een circulaire economie in Vlaanderen	

The different roadmaps covered different perspectives, product levels, spatial levels, and target types and targets. An overview of this variation is provided in Table 3.

Table 3. Variations in the different roadmaps

Roadmap	Perspective	Product level	Spatial level	Target type	Target
	Industry	Product group	Global	Absolute	GHG $emissions_{2040}$=0; non-circular resource $consumption_{2040}$=0
	Policy	All products	Regional	Absolute	GHG $emissions_{2050}$=minimal
	Policy	All products	Regional	Absolute	GHG $emissions_{2050}$=minimal
	Policy	All products	National	Absolute	GHG $emissions_{2030}$=minimal
	Policy	All products	International	Absolute	GHG $emissions_{2050}$=0
	Industry	Product group	Company	Relative	GHG $emissions_{2030}$=50% GHG $emissions_{2018}$
	Industry	Sector of products	International	Absolute	GHG $emissions_{2050}$=0
	Industry	One product	International	Relative	GHG $emissions_{2050}$=5-20% GHG $emissions_{1990}$

	Policy	All products	City	Relative	GHG $emissions_{2050}$=20% GHG $emissions_{2010}$
	Policy	Sector of products	Regional	Relative	GHG $emissions_{2050}$=20% GHG $emissions_{2005}$
	Policy	Multiple sectors	Regional	Absolute	Circular economy in 2050

3.2. Methodological framework

3.2.1. Types of scenario

The prospective technology assessment in the included roadmaps covers two types of scenarios. The first type is a 'current policies' scenario, also dedicated as a 'business-as-usual' scenario. In this scenario, no additional measures are implemented and the evolution of the system under study is estimated taking trends that would happen anyway into account. An example is the transition to renewable energy in the production of steel, required for cars in the roadmap of the automotive industry. An example of these two types of scenarios was found in the Deloitte roadmap, illustrated in Figure 9.

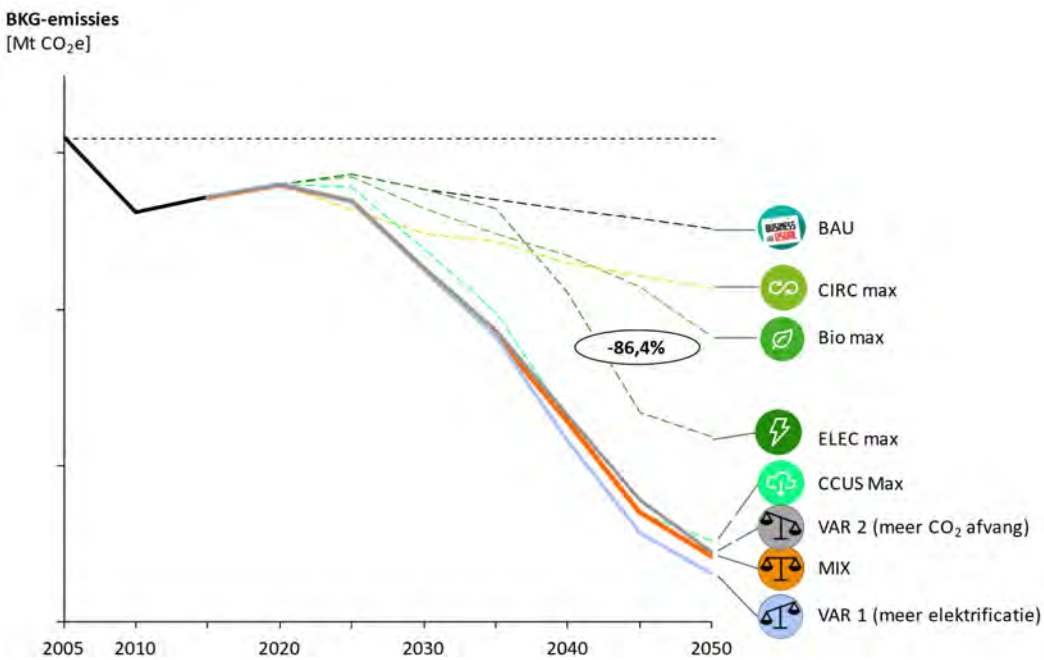


Figure 9. Current policies scenario (BAU) and improvement scenarios (CIRC max, BIO max, ELEC max, CCUS Max, Var 2, Mix, Var 1) (Deloitte, 2020)

To assess whether a specific measure in a specific scenario contributes to the target of the roadmap (f.e. minimal GHG emissions by 2050), corresponding indicators (f.e. GHG emissions in 2050) are quantified by the different roadmaps. The y-axis of Figure 9 illustrates such an indicator value. This indicator value can be influenced by multiple factors. For the review of the scenarios in the different roadmaps, four aspects of indicator value changes will be included:

the type of change, the type of effect, the type of technology, and the type of estimating the change.

3.2.2. Type of change

There are three main locations where the indicator value change can happen, leading to 7 different changes as can be seen in Figure 10.

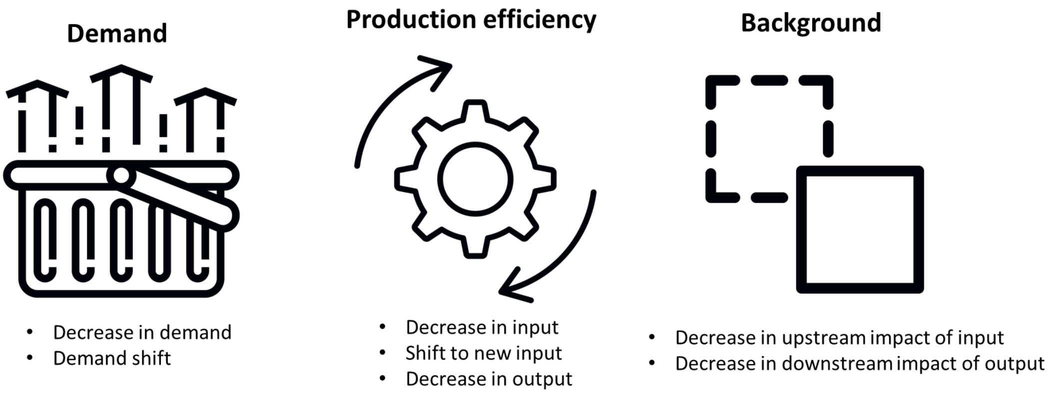


Figure 10. Where does the change happen?

The first location is the demand side, where both an increase or decrease as well as a demand shift to another technology or product can occur. The change can also happen due to an improved production efficiency of the technology itself, leading to a decrease in input, a shift to a new input, or a decrease in output, such as waste or emissions. The last place where the change can happen is in the background, outside of the specific scope of the roadmap. Improvements can happen both in the upstream impact of inputs, such as the carbon intensity of the electricity mix as well as in the downstream impact of outputs, due to improved recycling of waste materials.

3.2.3. Type of effect

The indicator value change can happen due to an indirect effect. For example, due to long-running trends or learning effects, or due to direct effects such as a specific measure limiting the allowed emissions of truck traffick Figure 11.

Figure 11. Why does the change happen?

3.2.4. Type of technology

The change can be caused by the implementation of new technologies or the implementation or optimization of existing technologies. If new technologies are involved, a difference can be made between technologies that are still in the research phase (TRL 1-8) and technologies that are ready to be implemented, but only have obtained a limited part of their market potential (TRL 9) (Figure 12).

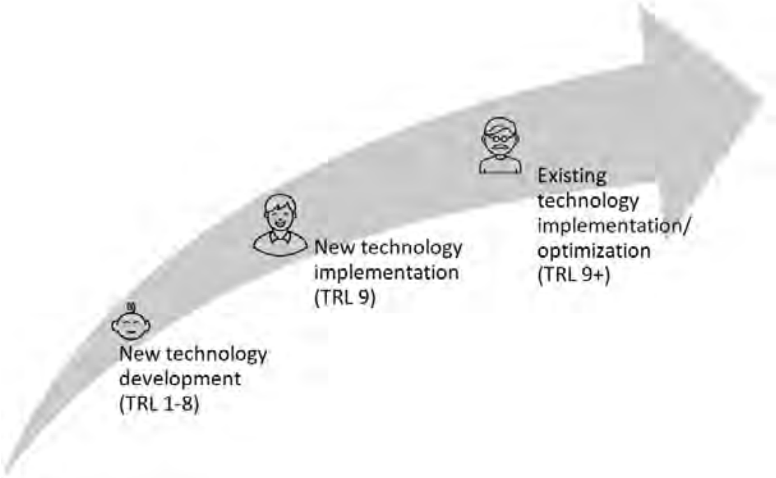


Figure 12. What drives the change?

3.2.5. Type of estimation

The indicator value change can be modeled in three ways. In the first approach, an expert estimate of a future value is used. In a second approach, an expert estimate of a yearly increase or decrease is implemented. In the third approach, historical data is extrapolated to obtain a future value or future increase or decrease (Figure 13).

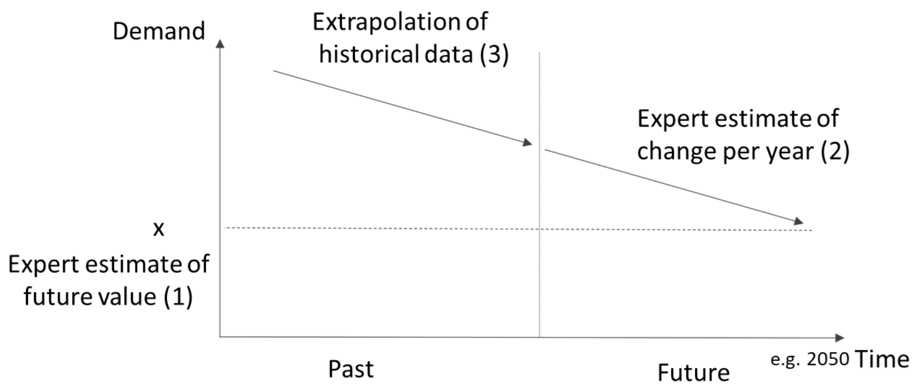


Figure 13. How is the change modeled?

3.3. Review results

In the following section, the review results for the eleven roadmaps will be discussed, categorized according to the seven change types, the two scenario types, the two effect types, the three technology types, and the three estimation types. A summary of all results is provided in Annex 1.

3.3.1. In-/decrease demand

A first way how an indicator value changes over time is due to higher or lower demand. Table 4 illustrates the type of scenario, effect, technology, and estimations included in the different roadmaps.

Table 4. Review results for in-/decrease in demand

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Current policies	Indirect	Mature	Expert estimate of value	
Current policies	Indirect	Mature	Expert estimate of change	
Improvement scenario	Indirect	Mature	Expert estimate of value	
Improvement scenario	Indirect	Mature	Expert estimate of change	
Improvement scenario	Direct	Mature	/	

In the current policies scenario, this in-/decrease in demand is often the projected market volume increase. In the Deloitte roadmap, assumptions were made for an increase in production in different sectors (Deloitte, 2020). For the improvement scenarios, this projected market volume increase can also be included as an indirect effect. In four roadmaps, the improvement scenarios also included a direct measure to in-/decrease the demand. This could be a decrease in car transport due to for example carpooling, more telework (ICEDD et al., 2021) or logistical improvements (Van Lier et al., 2019), or a decrease in air traffic (De Paep et al., 2019). An increase in demand for forestry was also included as a measure (European Commission, 2018). In the roadmaps of Deloitte (2020), World Economic Forum (2020), and Leuven 2030 (De Paep et al., 2019) a lifetime optimization of products was included, also leading to a decrease in demand. Figure 14 provides an example, where the road traffic is assumed to increase in both the current policies scenario and improvement scenario.

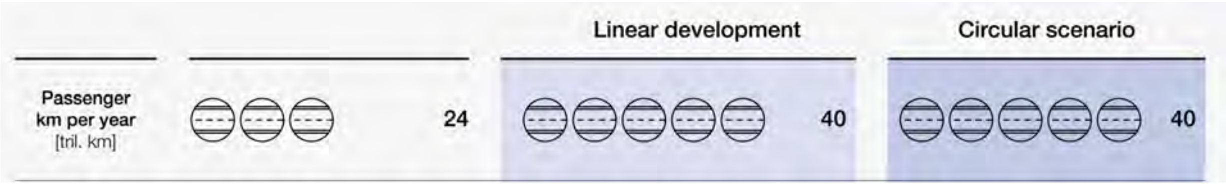
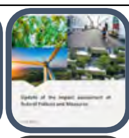
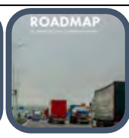
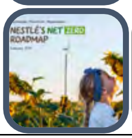


Figure 14. Example of an increase in demand for the current policies (Linear development) and improvement scenario (Circular scenario) (World Economic Forum, 2020)

3.3.2. Demand shift

A second change in the indicator value is induced by a shift in demand from one technology to another. Table 5 provides the results including the type of scenario, effect, technology, and estimation for the different roadmaps.

Table 5. Review results for demand shift

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Current policies	Indirect	Mature	Expert estimate of value	 
Current policies	Indirect	Mature	Extrapolation of historical data	
Improvement scenario	Direct	Mature	/	    

In the current policy scenario, demand shifts were estimated using both expert estimates of the value and extrapolation of historical data. The extrapolation of historical data was done by the ICEDD roadmap, to model the future demand for diesel, gasoline, and other vehicle types (ICEDD et al., 2021). For the improvement scenarios, multiple demand shifts were implemented by multiple roadmaps. Figure 15 provides an example of a demand shift in the transport mode in the Leuven city area where car transport is replaced by public transport in 2030.

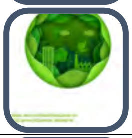
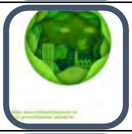
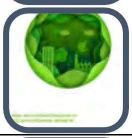
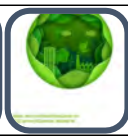
Transport in Leuven city region

Figure 15. Example of a demand shift, including existing technologies (De Paep et al., 2019)

3.3.3. Decrease in input demand

A third type of change was implemented in the production process itself. Here, a decrease in material or energy demand can lead to an improvement. If this is an indirect change, this can be considered a learning-by-doing effect. However, it is also possible that specific measures such as ecodesign specifications aim to stimulate this input decrease. The results for this measure are provided in Table 6.

Table 6. Review results for decrease in input demand

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Current policies	Indirect	Mature	Expert estimate of value	    
Current policies	Indirect	Mature	Expert estimate of change	
Current policies	Indirect	Mature	Extrapolation of historical data	
Improvement scenario	Indirect	Mature	Expert estimate of value	    
Improvement scenario	Indirect	Mature	Expert estimate of change	 

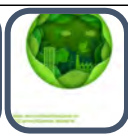
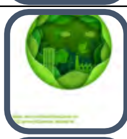
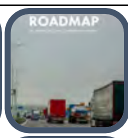
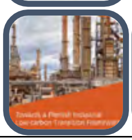
Improvement scenario	Direct	Mature	/	         

Six roadmaps included an increase in input also in the current policies scenario. All three estimation types were included. The extrapolation of historical data could be found in the ICEDD roadmap, where the effect of ecodesign and energy labeling measures on emission abatement was quantified: "*The BAU scenario (without ecodesign & energy labeling measures) is derived from extrapolating historical trends at the time of the first preparatory study analysis, including ongoing market trends in energy efficiency improvement and emissions abatement (VHK, 2019)*" (ICEDD et al., 2021). Almost all improvement scenarios included a decrease in input consumption. This was mostly due to higher energy efficiency.

3.3.4. Material shift

The fourth change in the indicator value is induced by the replacement of a material with a lower upstream environmental impact. The upstream environmental impact is the impact caused in the life cycle phases before the production process, for example, material extraction. The results are provided in Table 7.

Table 7. Review results for material shift

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Current policies	Indirect	Mature	Expert estimate of value	   
Current policies	Indirect	New (TRL 9)	Expert estimate of value	
Improvement scenario	Direct	Mature	/	     

				
Improvement scenario	Direct	New (TRL 9)	/	
Improvement scenario	Direct	New (TRL 1-8)	/	

Examples of a shift toward more environmentally-friendly inputs can be found in the Nestlé roadmap, where both existing technologies (sustainable ingredients), as well as new inputs (biogas-powered trucks), are available (Nestlé, 2021). In addition, the roadmap also takes new technologies into account to produce ‘net zero synthetic plastics’ made from CO_2 converted to hydrocarbons using renewable electricity. In the Eurofer (2019) roadmap, the material shift means a replacement of carbon with hydrogen or electricity as a reduction agent for the iron ore reduction stage. The “Clean planet for all” roadmap from the European Commission (2018) included multiple material shifts, being the electrification of current processes, the adoption of e-fuels, and the use of hydrogen.

Figure 16 provides an example of the Eurofer (2019) roadmap, where existing technologies are used in a material shift with the adoption of current projects and alternative pathways.

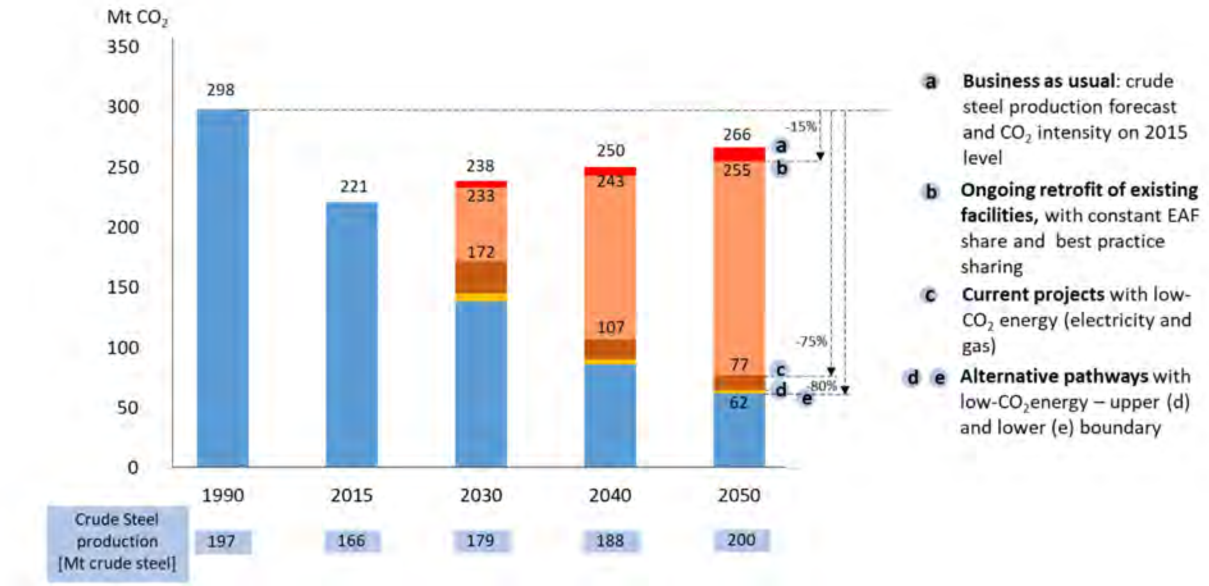


Figure 16. Example of a shift to better material including new technologies (Eurofer, 2019)

Figure 17 provides another example out of the Concawe (2021) roadmap, where a range of new technologies was included.

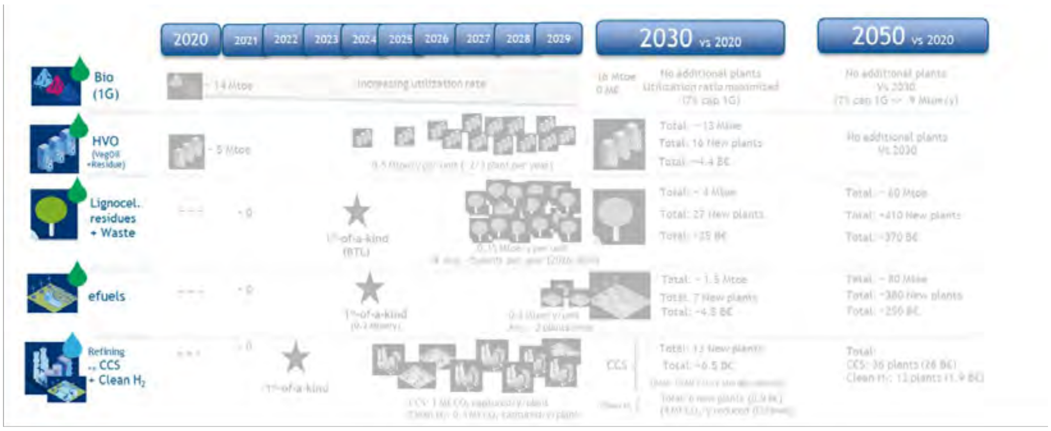
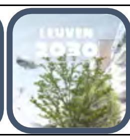


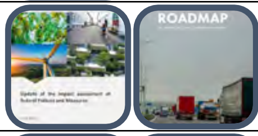
Figure 17. Example of a demand shift, including existing, new technologies at TRL 9 and new technologies at TRL (1-8) (Concawe, 2021)

3.3.5. Decrease in output

Due to the fifth change, the output is reduced. This output can cover direct emissions or waste materials. Table 8 provides the results for an output decrease.

Table 8. Results for output decrease

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Current policies	Indirect	Mature	Expert estimate of value	  
Current policies	Indirect	Mature	Expert estimate of change	

Improvement scenario	Indirect	Mature	Expert estimate of value	
Improvement scenario	Indirect	Mature	Expert estimate of change	
Improvement scenario	Direct	Mature	/	
Improvement scenario	Direct	New (TRL 9)	/	
Improvement scenario	Direct	New (TRL 1-8)	/	

An example of a direct decrease in output is due to lower emissions or less waste production. These lower emissions can be due to efficiency improvements in the technology itself (learning-by-doing) but also caused by the adoption of new technologies such as carbon capture and storage (CCS) or carbon capture and usage (CCU). Where CCS is considered to be a new technology at TRL9, CCU technologies are still considered to be in a lower TRL (1-8). However, the roadmap of Leuven 2030 also plans research for new CCS technologies (De Paep et al., 2019). The 'clean planet for all roadmap' included circular economy measures which were assumed to reduce waste production (European Commission, 2018).

An example of an indirect decrease in output is provided in Figure 18, where emission factors for different transport modes in 2030 were calculated based on efficiency improvements.

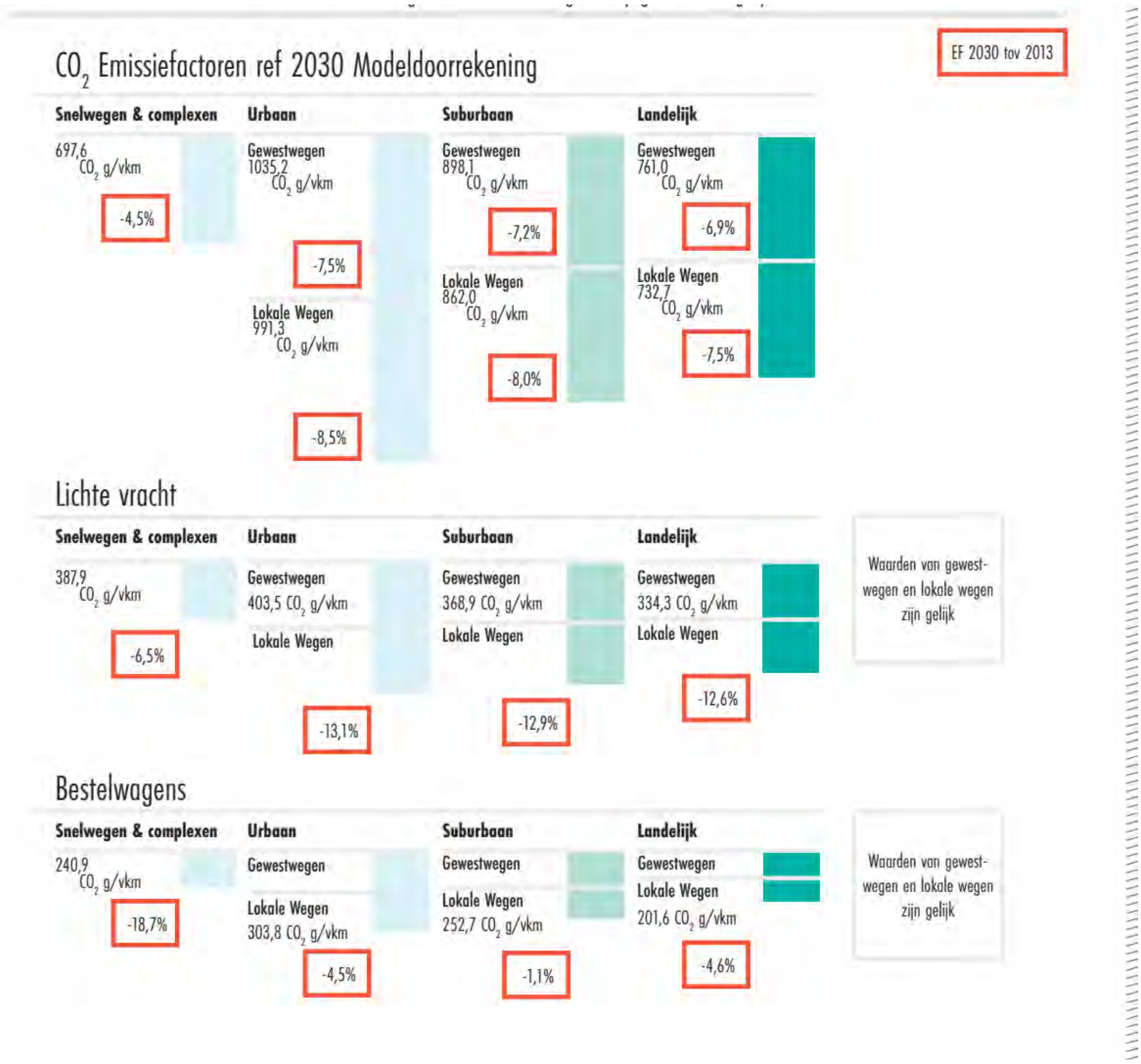


Figure 18. Example of a reduction in the output (Van Lier et al., 2019)

An example of an output reduction based on existing technologies is provided by the Nestlé (2021) roadmap and illustrated in Figure 19.

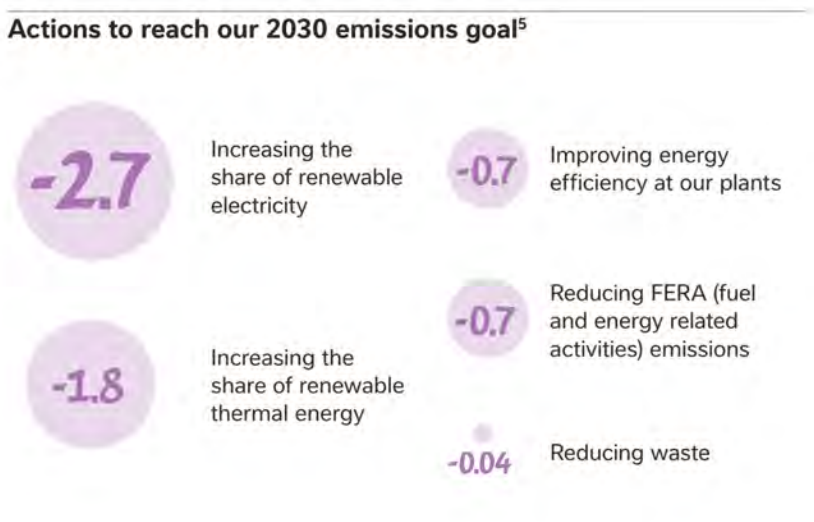
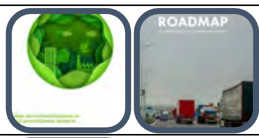
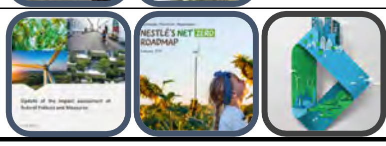


Figure 19. Example of a reduction output (Nestlé, 2021)

3.3.6. Decrease in upstream impact of the inputs

The eighth change occurs due to a change in the background. A decrease in the upstream impact of the inputs induces a lower indicator value. Table 9 provides an overview of the results.

Table 9. Results of a decrease in upstream impact of the inputs

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Current policies	Indirect	Mature	Expert estimate of value	
Current policies	Indirect	Mature	Extrapolation of historical data	
Current policies	Indirect	New (TRL 9)	Extrapolation of historical data	
Improvement scenario	Indirect	Mature	Expert estimate of value	
Improvement scenario	Direct	Mature	/	

An example of such an indirect decrease, which was adopted by most roadmaps in the improvement scenarios, was the decrease in the upstream environmental impact of the electricity mix to zero. The Eurofer roadmap assumes that the energy will be CO_2-free and thus further improvements will be made (Figure 20). This CO_2-free electricity mix was assumed to be available, so no direct measure is taken towards this. Another example of an indirect decrease in the upstream impact of the inputs was the shift to more local consumption of products. While the products themselves remain the same, the environmental impact decreases, with transport happening upstream (De Paep et al., 2019). An example of a direct effect can be found in the roadmap of Nestlé, where the suppliers are encouraged to become more energy efficient and prevent deforestation (Nestlé, 2021).

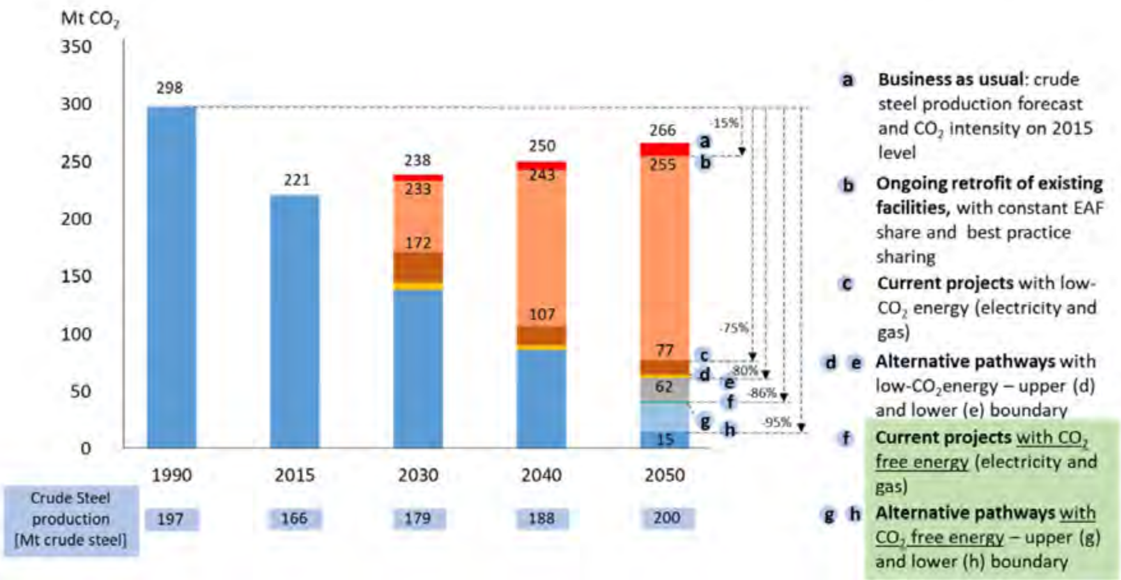
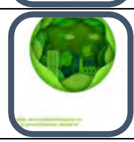


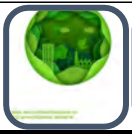
Figure 20. Example of the impact of decrease in the upstream impact (Eurofer, 2019)

3.3.7. Decrease in downstream impact outputs

The ninth change also occurs in the background, when the downstream impact of the outputs is decreased. This decrease can for example be due to improved recycling technology. Table 10 provides the results for this type of change.

Table 10. Results for a decrease in the downstream impact of the outputs

Type of scenario	Type of effect	Type of technology	Type of estimation	Roadmaps
Improvement scenario	Direct	Mature	/	
Improvement scenario	Direct	New (TRL 9)	/	

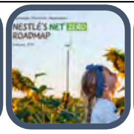
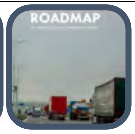
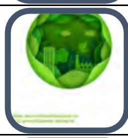
Improvement scenario	Direct	New (TRL 1-8)	/	 

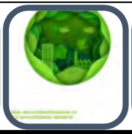
An example of a decrease in the downstream impact of the outputs is due to improved recycling practices if they are not considered inside the system of the covered company, product, sector, or region (De Paep et al., 2019; Nestlé, 2021). In the roadmap of Deloitte, also new technologies, such as chemical recycling are included (Deloitte, 2020). In the World Economic Forum (2020) roadmap, investments in new recycling technologies were included, but no further details were provided. For the Vlaanderen Circulair roadmap, no measures to decrease the downstream impact of the outputs were included, as the waste sector was included in the scope (therefore in the foreground and not in the background). In this case, a decrease in the downstream impact of the outputs would mean that measures would be taken to decrease the impact of further processing of the exported products or waste.

3.4. Learning effects for cost estimations in roadmaps

Learning effects also lead to a reduction in future costs of a technology. This can be due to lower consumption of materials or energy. However, also other costs may be reduced due to more efficient practices. The investment costs may also decrease over time, specifically for new technologies. Lastly, also price changes in the background can influence future cost estimates. Table 11 illustrates how the ten roadmaps included these future cost changes.

Table 11. Inclusion of technological costs in the roadmaps

Future technology costs	
Excluded	    
Included, but not clear how future changes are incorporated	
Included, efficiency improvements lead to lower operational costs (e.g. lower energy consumption leads to lower energy costs)	   
Included, additional operational costs decrease included	
Included, learning effects lead to lower investment costs in the future	 

Included, potential costs changes in the background (price changes)	   

The roadmap from the Departement Mobiliteit en Openbare Werken (Van Lier et al., 2019) and the ICEDD et al. (2021) roadmap did include cost estimates, but these were the government costs for the implementation of the specific plans and measures, not the costs of the technologies. The reduction in investment costs due to learning effects was estimated for some technologies in the Concawe (2021) roadmap, but not for all as the uncertainty on these numbers was too high. As the Concawe (Concawe, 2021) roadmap included fixed operational costs, this learning effect was also translated into operational costs. Figure 21 illustrates the future cost predictions of electrolyzers, including improvements.

Case	2030	2050
Efficiency %	70%	75%
Capacity Factor	85%	85%
Initial capex, $/kW-H_2$	1000	650
Fixed opex, % of capex	5%	5%

Note: based on lower heating values

Figure 21. Future technology costs in the Concawe roadmap (Concawe, 2021)

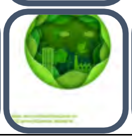
3.5. Application of the five recommendations

The next section will discuss how the five recommendations from the review of scientific publications were included in the roadmap studies. As the Vlaanderen Circulair roadmap did not include quantitative measures, it was excluded from this section.

3.5.1. Recommendation 1. Combine component and end product level

All roadmaps focused on the component level (Table 12). This result could be expected as most policy measures and improvement plans focus on the component level and not on the product level. No study estimated a learning effect directly on the end product level. This means that the learning effects can be underestimated. However, as the aim of the roadmaps was to assess how specific measures change an indicator value, a conservative approach, where underestimation is preferred to overestimation, is desirable.

Table 12. Results for recommendation 1

Level	Roadmaps
Component level	         

End product level	
Combination	

3.5.2. Recommendation 2. Combine technical and economic/environmental dimension

All roadmaps included effects in the technical dimension (Table 13). Six of the roadmaps also made assumptions in the environmental dimension, for example by assuming the global warming impact of the electricity mix to be zero in the future. None of the roadmaps combined both approaches. Similar to recommendation 1, this can lead to an underestimation of the results.

Table 13. Results for recommendation 2

Level	Roadmaps
Technical level	
Environmental level	
Combination	

3.5.3. Recommendation 3. Combine extrapolated and projected values

All roadmaps included projected values (Table 14). Only the ICEDD roadmap also included extrapolated values. No roadmap included both approaches to obtain a value for a future estimate.

Table 14. Results for recommendation 3

Level	Roadmaps
Projected values	
Extrapolation	
Combination	

3.5.4. Recommendation 4. Combine learning-by-doing and learning-by-searching

All roadmaps included learning-by-doing effects, which were interpreted as indirect effects leading to a decrease in input consumption, output consumption, or background impact. If learning-by-searching is interpreted as the improvement by means of the introduction of new technologies, all roadmaps, except for the Nestlé roadmap included learning-by-searching effects. The Nestlé roadmap also mentioned new technologies but on a 2050 horizon instead of a 2030 horizon. As both learning effect types were included, we can conclude that this recommendation was better followed in roadmaps than in the scientific literature. This can be explained by the difficulty of including learning-by-searching effects due to new technologies if the learning effect is only estimated on an end product level in the environmental dimension, which was often the case in scientific publications. As roadmaps follow a more technical perspective, focussing on the components, it is much easier to make assumptions about the performance of new technologies.

Table 15. Results for recommendation 4

Learning effect typ	Roadmaps
Learning-by-doing	
Learning-by searching	

3.5.5. Recommendation 5. Follow the tier-based method with quality criteria

None of the roadmaps discussed the quality of the estimates. A tier-based method was therefore not applied. Only one roadmap, the ICEDD roadmap, discussed the uncertainty of its assumptions, by providing three potential scenarios for each improvement scenario. These three scenarios included a worst-case, best-case, and likely scenario, as can be seen in the example in Figure 22. For the cost prediction, a range of the predictions of future costs was also provided by the Deloitte, Concawe, and Eurofer roadmap.

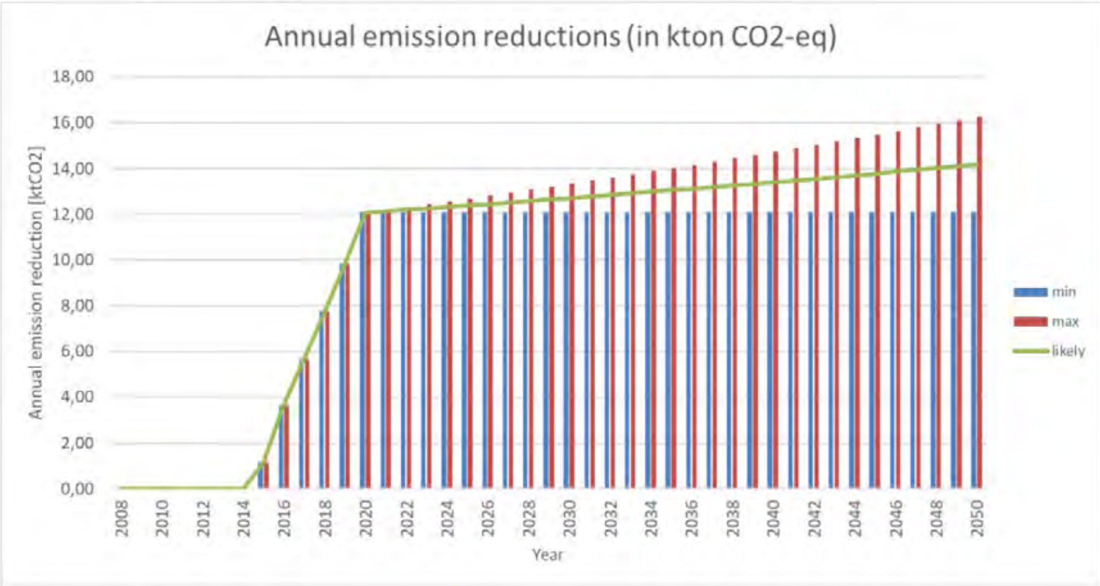


Figure 22. Uncertainty in the ICEDD roadmap (ICEDD et al., 2021)

4. Reflections and recommendations

The results of these study are valuable to different stakeholders. First, they can provide guidance and reference points for future roadmaps to authors of these roadmaps. Secondly, they can assist in interpreting the roadmaps and the included or excluded strategies. Thirdly, the results may be valuable to a broader audience, to get a perspective on where roadmaps expect changes to occur. For future roadmaps, three main recommendations can be formulated.

The first recommendation is to **make use of historical data**, when available. Most roadmaps only relied on expert estimates for future predictions. Some trends, such as learning effects of technologies that have recently entered the market, might already be ongoing. Historical data can help frame expected improvements and provide information on expected maximum values in improvements. This way, a potential lock-in can be estimated.

The second recommendation stresses the importance of **including background changes**. Roadmaps follow a prospective perspective as they try to provide a look into the future. However, the future does not include only changes in the system under study. Also changes in the background might occur and can have a large impact on the results. This was incorporated by most roadmaps by applying a zero CO_2 emission factor to the electricity mix. Although this is a clear inclusion of a background effect, a zero CO_2 electricity mix is very optimistic and even utopian as the materials required for energy production technologies also have an impact. As the required recycling technologies are not yet on a commercial level, this can have a large impact on the results, while this hasn't been discussed by any of the roadmaps. Care should therefore be taken on what to assume as a future environmental impact in the background.

The third recommendation advises to **include scenarios** to obtain more information on the potential range of results due to uncertainty issues. Making predictions encompasses a large level of uncertainty. The inclusion of scenarios can help in providing a range of indicator scores and illustrating the impact of certain choices.

Besides these three recommendations, a critical reflection on technological learning in roadmaps is formulated. Technological learning incorporates the improvement of a technology. However, **the increase of this performance improvement decreases over time** (Junginger et al., 2010). This means that solemnly focussing on learning effects to decrease costs and environmental impacts in the future, will not be enough. On the contrary, learning effects as a main strategy for improvement may lead to lock-in, which hampers the required transition to a circular economy. As was shown by the roadmaps, learning effects typically occurring in the improvement of product efficiency in both foreground and background were mostly not the only implemented changes. Decreasing demands or demand shifts such as a decrease in airport traffic and the modal shift towards more public transport, as discussed in the Leuven 2030 roadmap, are necessary elements for this transition as well.

A transition to a circular economy has the ambition to reduce environmental impacts by reducing the need for primary materials and the impact caused by certain waste practices. This way, it is a means to an end, this end being a more sustainable society. It is therefore not surprising that most roadmaps focus on a reduction of the environmental impacts themselves, being a climate neutral company, city, or region. The importance of a circular economy for this goal was only stressed by a few roadmaps. An exception was the roadmap of Vlaanderen Circulair which states a circular economy as the main target. While this focus on a circular economy makes it more tangible what kind of measures are required, it is important not to exclude the end goal, being a more sustainable society, as a more circular economy does not automatically lead to a more sustainable society.

Looking at the different places where a measure could have an impact, measures aiming for a circular economy can tick all the boxes. According to PBL, these measures can be summarized in four main strategies (Hanemaaijer et al., 2021), illustrated in Figure 23 (Konietzko et al., 2020):

- **Narrow the loop**: producing fewer products (e.g. product sharing) or producing more efficiently with fewer resources: this is similar to the **demand decrease** strategy and the **input decrease** strategy used in the roadmaps
- **Slow the loop**: extend the lifetime of products (e.g. reuse, repair); this also induces a **demand decrease** for the product
- **Close the loop**: recycling of materials so fewer primary materials are required: this mainly relates to an **output decrease** by, for example, carbon capture and usage or more recycling.
- **Substitution** towards renewable resources: this relates to the **demand shift** and the **material shift**. However, in the current study, both shifts included a shift towards a product or material with a lower environmental impact. This shift was therefore not restricted to renewable resources, although this was often the case (e.g. biofuels, renewable energy, clean hydrogen).

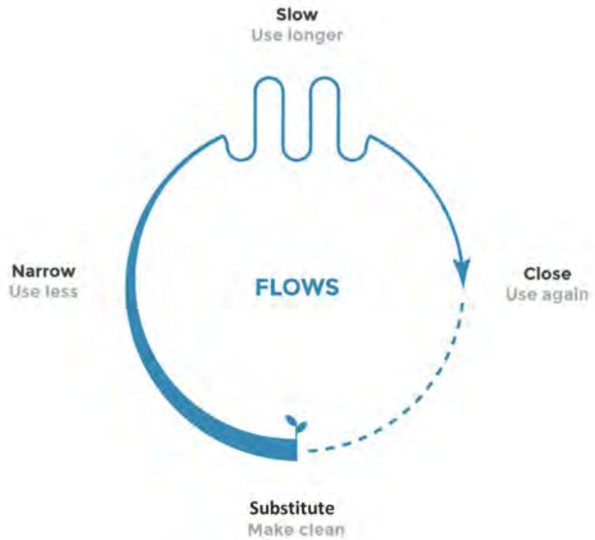


Figure 23. The four circular economy strategies, adapted from (Konietzko et al., 2020)

Taking the economy as a whole, there is no division between background and foreground changes. The background strategies are therefore only important when the roadmap focuses on (a selection of) products, which was the case for all roadmaps. In addition, background effects are often indirect effects and can therefore not be targeted as a specific measure.

However, as was done in the Nestlé roadmap, suppliers in the background can be stimulated to provide more sustainable practices. In this way, also direct effects aiming to improve background processes can be possible.

As all of the improvement measures could be related to these four circular economy strategies, it is surprising that the concept of circular economy was mentioned only in a few roadmaps.

Technological learning effects [1] are mostly used for production efficiency improvement regarding energy or resource consumption (narrow the loop/input decrease). However, also for the 'slow the loop' and 'close the loop' strategies, learning effects could occur. For example, we could expect products to last longer when they have been produced more, as feedback on what induces early fall-out can improve the production process. This is an example of learning-by-interacting. However, this will only happen if an increased product lifetime is in the interest of the producer. Learning effects can help us become better in a certain process when we practice it more. However, for a circular economy to profit from the merits of learning effects, we should first ensure we have the right process in place and the right definition of 'better' before learning effects can play their role.

[1] In this study, learning effects in technology have been studied. However, the concept of learning can be interpreted on different levels. On a more sociological/social level, learning in sustainability transitions has also extensively been studied. A review of the current literature on this topic can be found in van Mierlo B., Beers P.J., 2020. Understanding and governing learning in sustainability transitions: A review. Environmental Innovation and Societal Transitions 34, 255-269. https://doi.org/10.1016/j.eist.2018.08.002.

5. Specific recommendations for the Vlaanderen Circulair roadmap

For the Vlaanderen Circulair roadmap, it was observed that most of the measures were included in a descriptive, qualitative way. Only a decrease in the downstream impact of products was not discussed. For a further elaboration of quantitative scenarios, the best-practices from the other roadmap studies and the above mentioned recommendations can be used to estimate the effect of specific measures and scenarios on specific indicators. This includes the definition of multiple scenarios, among which a benchmark scenario; specific targets to monitor; the quantification of effects on demand, production efficiency, and the background, which can be based on the qualitative measures already discussed in the roadmap; the inclusion of both direct effects related to a measure and indirect effects which will happen regardless of the adoption of the specific measure; the inclusion of learning effects when assessing the impact of technologies that are not yet fully mature or commercialized on a large scale; and the use of both historical data and expert estimates. Scenario analyses, using the indicators from the CE monitor, can be used for this purpose.

For example, for the different working agendas, the effect of specific plans and measures on the material reduction target of 30% by 2030 could be assessed. These measures can cover production efficiency improvements, demand changes, or changes in the background. A scenario on the implementation of the specific measure could be compared with a benchmark scenario, taking into account other future trends such as the renewable energy transition, which will also affect the material footprint target, for example. If the specific measure requires new technologies, learning effects could be included. In addition, for existing technologies, historical data on for example efficiency improvements can assist to estimate future expected efficiency improvements. Expert opinions will need to be consulted to establish assumptions on such future values, where worst-case and best-case scenarios could be included in the scenario analyses. As the renewable energy transition requires new materials and security of supply should be safeguarded, an interesting example of a measure to assess would be improved recycling practices for renewable energy technologies. Scenario analysis could look at different scenarios, including a business-as-usual without additional incentives, to assess the impact of improved recycling facilities on the material footprint reduction target of 30% by 2030.

6. Conclusions

In this study, the inclusion of learning effects in roadmaps was discussed, using a methodological framework based on an extensive review of the use and calculation of learning effects in prospective technology assessment. No general methodological approach towards roadmap construction was found. This study aims to fill this gap and provide guidance for future roadmaps, extending beyond the concept of learning effects. As a circular economy is an important stepping stone moving toward a sustainable society, prospective assessments on how to obtain a more circular economy are required. However, as a circular economy is a means to an end, the end goal, being a more sustainable society, should still be taken into account.

This link between the circular economy and sustainability issues such as climate change should be made more tangible as all measures that were found to be included in the roadmaps could be classified as circular economy measures. However, this link was not discussed by the roadmaps themselves. In addition, for future effects in the background, such as the renewable energy transition, material-related aspects such as the impact of extraction and recycling were ignored. This leads to an underestimation of the impacts in future scenarios included in the roadmaps.

For the construction of future sustainability roadmaps, the main take-away messages for this study are:

- A generic framework for roadmap construction was proposed
- The link between a circular economy and sustainability should better be stated, where circular economy measures are used as a means to an end
- Learning effects can and should be included to incorporate future technological evolution
- Material related impacts should be included for future trends such as the renewable energy transition
- Changes in the background should be included when looking at future scenarios
- Historical data to quantify trends that will happen independently of newly adopted measures should be used when available
- Different scenarios, including a benchmark scenario, should be used to provide a range on the indicator value instead of a one-point estimate

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Annex 1. Summary review

Table A1. Overview of included and excluded measures in the review

Type of change[a]	Type of scenario	Type of effect	Type of technology (TRL)	Type of estimation[b]	Roadmaps included[c]
Demand +-	Current policies	Indirect	9+	Value	2,3,5,6,7,8,10
Demand +-	Current policies	Indirect	9+	Change	2,7
Demand +-	Current policies	Indirect	9+	Extrapolation	
Demand +-	Improvement	Indirect	9+	Value	3,5,6,8,10
Demand +-	Improvement	Indirect	9+	Change	2,7
Demand +-	Improvement	Indirect	9+	Extrapolation	
Demand +-	Improvement	Direct	9+	Value	3,4,6,7,8,9
Demand ↔	Current policies	Indirect	9+	Value	3,8
Demand ↔	Current policies	Indirect	9+	Change	
Demand ↔	Current policies	Indirect	9+	Extrapolation	9
Demand ↔	Current policies	Indirect	9	Value	
Demand ↔	Current policies	Indirect	9	Change	
Demand ↔	Current policies	Indirect	9	Extrapolation	
Demand ↔	Current policies	Indirect	1-8	Value	
Demand ↔	Current policies	Indirect	1-8	Change	
Demand ↔	Current policies	Indirect	1-8	Extrapolation	
Demand ↔	Improvement	Indirect	9+	Value	
Demand ↔	Improvement	Indirect	9+	Change	
Demand ↔	Improvement	Indirect	9+	Extrapolation	
Demand ↔	Improvement	Indirect	9	Value	
Demand ↔	Improvement	Indirect	9	Change	
Demand ↔	Improvement	Indirect	9	Extrapolation	
Demand ↔	Improvement	Indirect	1-8	Value	
Demand ↔	Improvement	Indirect	1-8	Change	
Demand ↔	Improvement	Indirect	1-8	Extrapolation	
Demand ↔	Improvement	Direct	1-8	Value	
Demand ↔	Improvement	Direct	9	Value	
Demand ↔	Improvement	Direct	9+	Value	3,5,8,9
Input +-	Current policies	Indirect	9+	Value	1,2,3,4,7
Input +-	Current policies	Indirect	9+	Change	7
Input +-	Current policies	Indirect	9+	Extrapolation	9
Input +-	Current policies	Indirect	9	Value	
Input +-	Current policies	Indirect	9	Change	
Input +-	Current policies	Indirect	9	Extrapolation	
Input +-	Current policies	Indirect	1-8	Value	
Input +-	Current policies	Indirect	1-8	Change	
Input +-	Current policies	Indirect	1-8	Extrapolation	
Input +-	Improvement	Indirect	9+	Value	1,2,4,7,9

Input +-	Improvement	Indirect	9+	Change	7,9
Input +-	Improvement	Indirect	9+	Extrapolation	
Input +-	Improvement	Indirect	9	Value	
Input +-	Improvement	Indirect	9	Change	
Input +-	Improvement	Indirect	9	Extrapolation	
Input +-	Improvement	Indirect	1-8	Value	
Input +-	Improvement	Indirect	1-8	Change	
Input +-	Improvement	Indirect	1-8	Extrapolation	
Input +-	Improvement	Direct	9+	Value	1,2,3,4,5,7,8,9,10
Input +-	Improvement	Direct	9	Value	
Input +-	Improvement	Direct	1-8	Value	
Input ↔	Current policies	Indirect	9+	Value	1,3,4,7
Input ↔	Current policies	Indirect	9+	Change	
Input ↔	Current policies	Indirect	9+	Extrapolation	
Input ↔	Current policies	Indirect	9	Value	7
Input ↔	Current policies	Indirect	9	Change	
Input ↔	Current policies	Indirect	9	Extrapolation	
Input ↔	Current policies	Indirect	1-8	Value	
Input ↔	Current policies	Indirect	1-8	Change	
Input ↔	Current policies	Indirect	1-8	Extrapolation	
Input ↔	Improvement	Indirect	9+	Value	
Input ↔	Improvement	Indirect	9+	Change	
Input ↔	Improvement	Indirect	9+	Extrapolation	
Input ↔	Improvement	Indirect	9	Value	
Input ↔	Improvement	Indirect	9	Change	
Input ↔	Improvement	Indirect	9	Extrapolation	
Input ↔	Improvement	Indirect	1-8	Value	
Input ↔	Improvement	Indirect	1-8	Change	
Input ↔	Improvement	Indirect	1-8	Extrapolation	
Input ↔	Improvement	Direct	9+	Value	1,2,3,4,5,7,8,9
Input ↔	Improvement	Direct	9	Value	1,2,4,5,7,8,9,10
Input ↔	Improvement	Direct	1-8	Value	1,2,4,7,8,10
Output +-	Current policies	Indirect	9+	Value	3,4,8
Output +-	Current policies	Indirect	9+	Change	8
Output +-	Current policies	Indirect	9+	Extrapolation	
Output +-	Current policies	Indirect	9	Value	
Output +-	Current policies	Indirect	9	Change	
Output +-	Current policies	Indirect	9	Extrapolation	
Output +-	Current policies	Indirect	1-8	Value	
Output +-	Current policies	Indirect	1-8	Change	
Output +-	Current policies	Indirect	1-8	Extrapolation	
Output +-	Improvement	Indirect	9+	Value	8
Output +-	Improvement	Indirect	9+	Change	8,9
Output +-	Improvement	Indirect	9+	Extrapolation	

Output +-	Improvement	Indirect	9	Value	
Output +-	Improvement	Indirect	9	Change	
Output +-	Improvement	Indirect	9	Extrapolation	
Output +-	Improvement	Indirect	1-8	Value	
Output +-	Improvement	Indirect	1-8	Change	
Output +-	Improvement	Indirect	1-8	Extrapolation	
Output +-	Improvement	Direct	9+	Value	1,2,3,4,5,6,7,8,10
Output +-	Improvement	Direct	9	Value	2,3,7,8,10
Output +-	Improvement	Direct	1-8	Value	1,2,3,6,7,8,10
USI input +-	Current policies	Indirect	9+	Value	
USI input +-	Current policies	Indirect	9+	Change	7,8
USI input +-	Current policies	Indirect	9+	Extrapolation	9
USI input +-	Current policies	Indirect	9	Value	
USI input +-	Current policies	Indirect	9	Change	
USI input +-	Current policies	Indirect	9	Extrapolation	9
USI input +-	Current policies	Indirect	1-8	Value	
USI input +-	Current policies	Indirect	1-8	Change	
USI input +-	Current policies	Indirect	1-8	Extrapolation	
USI input +-	Improvement	Indirect	9+	Value	1,2,3,4,6,7,8,10
USI input +-	Improvement	Indirect	9+	Change	
USI input +-	Improvement	Indirect	9+	Extrapolation	
USI input +-	Improvement	Indirect	9	Value	
USI input +-	Improvement	Indirect	9	Change	
USI input +-	Improvement	Indirect	9	Extrapolation	
USI input +-	Improvement	Indirect	1-8	Value	
USI input +-	Improvement	Indirect	1-8	Change	
USI input +-	Improvement	Indirect	1-8	Extrapolation	
USI input +-	Improvement	Direct	9+	Value	5,9
USI input +-	Improvement	Direct	9	Value	
USI input +-	Improvement	Direct	1-8	Value	
DSI output +-	Current policies	Indirect	9+	Value	
DSI output +-	Current policies	Indirect	9+	Change	
DSI output +-	Current policies	Indirect	9+	Extrapolation	
DSI output +-	Current policies	Indirect	9	Value	
DSI output +-	Current policies	Indirect	9	Change	
DSI output +-	Current policies	Indirect	9	Extrapolation	
DSI output +-	Current policies	Indirect	1-8	Value	
DSI output +-	Current policies	Indirect	1-8	Change	
DSI output +-	Current policies	Indirect	1-8	Extrapolation	
DSI output +-	Improvement	Indirect	9+	Value	
DSI output +-	Improvement	Indirect	9+	Change	
DSI output +-	Improvement	Indirect	9+	Extrapolation	
DSI output +-	Improvement	Indirect	9	Value	
DSI output +-	Improvement	Indirect	9	Change	

DSI output +-	Improvement	Indirect	9	Extrapolation	
DSI output +-	Improvement	Indirect	1-8	Value	
DSI output +-	Improvement	Indirect	1-8	Change	
DSI output +-	Improvement	Indirect	1-8	Extrapolation	
DSI output +-	Improvement	Direct	9+	Value	2,3,4,5,6,10
DSI output +-	Improvement	Direct	9	Value	7
DSI output +-	Improvement	Direct	1-8	Value	6,7

[a]: Demand +-= Demand in/decrease; Demand ↔= Demand shift; Input +-= Input in-/decrease; Input ↔= Input shift; Output +-= Output in-/decrease; USI input +-= Upstream impact of the inputs; DSI output +-= Downstream impact of the outputs.
[b]: Value= Expert estimate of value; Change= Expert estimate of change; Extrapolation= Extrapolation from historical data.
[c]: 1= Concawe roadmap (Concawe, 2021); 2= Departement Omgeving roadmap (Vlaamse Overheid Departement Omgeving, 2018); 3= Leuven 2030 roadmap (De Paep et al., 2019); 4= ”A clean planet for all” roadmap (European Commission, 2018); 5= Nestlé roadmap (Nestlé, 2021); 6= World Economic Forum roadmap (World Economic Forum, 2020); 7= Deloitte roadmap (Deloitte, 2020); 8= Departement Mobiliteit & Openbare werken roadmap (Van Lier et al., 2019); 9= ICEDD roadmap (ICEDD et al., 2021); 10= Eurofer roadmap (Eurofer, 2019).

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