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Citation

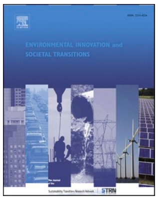
Koese, J. M., Blanco Rocha, C. F., Breeman, G. E., & Vijver, M. G. (2022). Towards a more resource-efficient solar future in the EU: an actor-centered approach. *Environmental Innovation And Societal Transitions*, *45*, 36-51. doi:10.1016/j.eist.2022.09.001

Environmental Innovation and Societal Transitions 45 (2022) 36–51

Contents lists available at ScienceDirect

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist



Research article

Towards a more resource-efficient solar future in the EU: An actor-centered approach

Maarten Koese[a], Carlos F. Blanco[a,*], Gerard Breeman[b], Martina G. Vijver[a]

[a] *Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, the Netherlands*
[b] *Institute of Public Administration, Leiden University, P.O. Box 13228, 2501 EE Den Haag, the Netherlands*

ARTICLE INFO

Keywords:
Energy transition
Circular economy
Critical materials
Actor-centered institutionalism
Science-policy interface
Photovoltaics

ABSTRACT

Material constraints may slow the pace of energy transition if the materials intensity of renewable energy technologies remains the same. Innovations in solar photovoltaics (PV) can contribute to achieving lower material demands. In this research, the actor-centered institutionalism framework, transitions literature and the science-policy interface framework are used to analyze how the involved actors perceive the transition towards more resource-efficiency in solar PV, what their preferences are, and how government should support this transition. Altogether, resource-efficiency is not sufficiently supported, while it is considered extremely important in the future of solar PV according to various involved actors. Traditional silicon-based solar panels are locked-in into the current policy landscape. Actors prioritizing resource-efficiency interact in a niche space, while actors involved in traditional silicon-based PV form the regime. Improved alignment between science and policy actors would help ease disagreements and prevent or benefit from path-dependency, thus, supporting resource-efficiency in solar PV.

1. Introduction

The green energy transition leads to increasing material demands, today and in the near future (IEA, 2021a). Material constraints will obstruct the energy transition if the material intensity of green energy technologies remains the same (Sprecher and Kleijn, 2021). While traditional silicon-based solar cells are continuously developing and the amounts of materials required for their production has decreased during the past years (Green, 2018; Stamford and Azapagic, 2018), material depletion is still a serious risk due to the increasing demand for these technologies (IEA, 2021a). Evidently, resource-efficiency in solar photovoltaics (PV) must increase to prevent depletion of material resources. In this paper, circularity is defined as preserving resources inside the economy (Lieder and Rashid, 2016; Bocken et al., 2016). Simultaneously, material use should be considered while growing the capacity of renewable energy technologies, to prevent material depletion, supply risks and consequently a stagnating energy transition in the future (Graedel et al., 2015; Sprecher and Kleijn, 2021). This means material intensity, i.e., the amounts of materials required in a product, in solar PV should decline to be able to increase solar PV capacity without risking future problems. In this paper, both increasing circularity and reducing material intensity are considered important pathways to achieve resource-efficiency in solar PV.

Materials in solar PV will have to be used and re-used consciously (Bobba et al., 2020). The amounts of critical materials in silicon-based solar PV have decreased drastically in the past decades, and are expected to decline further in the future (Woodhouse et al., 2019). However, since these cells account for around 90% of total market share (Wilson et al., 2020) they still lead to very large

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* Corresponding author.
E-mail address: c.f.blanco@cml.leidenuniv.nl (C.F. Blanco).

https://doi.org/10.1016/j.eist.2022.09.001
Received 9 November 2021; Received in revised form 7 September 2022; Accepted 8 September 2022

material requirements, especially with the predicted solar PV market growth. Thin film technologies, e.g., CdTe (cadmium telluride) or CIGS (copper indium gallium diselenide) solar cells, responsible for around 7–8% of total solar PV market share in 2014, contain critical minerals like cadmium and indium (Lee and Ebong, 2016). Finally, emerging solar PV technologies, like perovskites, III-V cells and tandem cells, are responsible for the modest remaining part of the market share. These technologies (see Polman et al., 2016) are very promising, because their efficiencies are not yet approaching Shockley-Queisser (S-Q) limits, which refers to the theoretical efficiency that these solar cells can reach. Perovskites, although raising toxicity concerns due to their lead content, do not contain any materials classified as critical. III-V solar cells, contain critical minerals like gallium and germanium. Tandem cells, in which these emerging solar PV cells are combined with a silicon-based solar cell, consist of a silicon layer in combination with the emerging technology (Wilson et al., 2020). Many of the elements currently used in (emerging) solar PV technologies, will be depleted in the next 5 to 50 years (Hunt et al., 2015). Solar PV producers thus must work towards further material efficiency, re-use and recycling to prevent problems in the future.

The predicted growth in the use of solar panels in the coming decades (IEA, 2021b; Chowdhury et al., 2020) combined with the expected start of large-scale recycling of solar PV around 2035 (CE Delft, 2021) show the urgency of developing effective solar PV resource-efficiency policies. This involves action at the technical level, in improved solar PV designs and the development of technologically feasible recycling processes. It also requires a transition at the social, political, and institutional levels, in the development of knowledge networks, appropriate regulations, and effective policies related to more resource-efficient solar PV. These should accommodate and support technological innovations such as the development of emerging technologies and reduced material intensity in silicon-based cells.

The transition at this institutional level will be the focus of this paper. Both national governments as well as EU institutions play a role. To analyze how the involved actors perceive resource-efficiency in solar PV and whether they believe the current policies sufficiently resource-efficiency in solar PV, the following research question was formulated:

What are the perceptions, preferences and capabilities of the involved stakeholders regarding the transition to more resource-efficient solar PV within the existing policy landscape?

This question will be addressed by using the actor-centered institutionalism (ACI) framework (Scharpf, 1997). This framework analyzes how actors perceive a policy challenge, what their preferences for solutions and outcomes are, and what conflicts may potentially arise among involved actors. Additionally, a transitions perspective will be used to analyze the shift to more resource-efficient solar PV (Markard et al., 2012; Köhler, 2019). Scientific actors, governmental actors and involved stakeholders are already working together on this transition (CE Delft, 2021; Kerp and Jönsthövel, 2021). Since science plays a large role in determining effective policy solutions in such an innovative and science-based sector, science-policy interface literature (Turnhout et al., 2016; Sundqvist et al., 2018; Sokolovska et al., 2019; Hukkinen, 2020), which refers to the exchange and joint development of knowledge used in policy processes (Sokolovska et al., 2019), will be applied to further analyze this transition.

The contents of this article are organized as follows: we provide an overview of the technical approaches to increase resource-efficiency in solar PV and describe the theoretical background of sustainability transitions, the ACI framework and science-policy interface in section two. We present the used methods in section three, followed by the results of the policy and actor analysis in section four. These results are interpreted in section five, while section six includes our main findings and concluding remarks.

2. Theory

A shift to a more resource-efficient solar PV sector is part of a larger transition towards a green energy system. Such a transition requires changes along different dimensions, ranging from technological to institutional and socio-cultural, and it involves many different actors (Markard et al., 2012). There are several ways to improve resource-efficiency of current and future PV technologies. Four examples are presented here, of which the first two entail reducing (relative) material intensity, while the latter two relate to increasing circularity.

(1) A reduction in the quantity of materials used in the manufacturing of PV cells. Some examples include the progressive reduction in silicon wafer thickness from 280 to 170 microns, or the replacement of the silicon wafer altogether by thin-film (micron-thick) layers of alternative materials such as cadmium telluride (Polman et al, 2016; Wilson et al., 2020; Woodhouse et al., 2020).

(2) The design of more efficient cells, which reduces the material intensity not per panel but per kWh of electricity generated. Some of the high-efficiency PV cells currently being developed can convert 40% more energy from sunlight than conventional silicon cells (Polman, 2016; Wilson et al., 2020). This directly translates to a smaller panel area and less materials required per kWh. However, the effectiveness of this performance enhancement in reducing total materials demand is potentially compromised by a ‘rebound effect’ (Sorrell, 2007), where more efficient cells are highly successful, and their demand thus increases considerably. This paradoxically may lead to a higher total material demand as a consequence of solar PV implementation.

(3) The development of recycling techniques for existing solar panels. To date these techniques have largely focused on conventional silicon PV, because of the large market share. These recycling techniques, however, were developed retroactively and face challenging technical, economic and environmental constraints which hinder their implementation (Latunussa et al., 2016; Kumar et al., 2017). Currently, only bulk materials that are easily separated, such as glass and aluminum, are being recovered. More advanced recycling techniques, which aim at recovering silicon and other more valuable materials, are still under development and have not been proven technically and economic feasibility at large scale.

(4) The ‘circular-by-design’ or ‘design-to-deconstruct’ approach (Braungart et al., 2007; Van den Berg and Bakker, 2015; Vanegas et al., 2018; Desing et al., 2021). Following the safe-by-design concept (Van de Poel and Robaey, 2017), this approach aims at designing and assembling cells and panels in a way that facilitates their disassembly and materials separation once they reach their

end-of-life.

While the recycling approach is a required reaction to deal with a first wave of PV waste, the other three approaches are likely to have a more important role in managing resource-efficiency of PV life cycles in the future, since they influence the design of the cells (Charles et al., 2016).

In the context of sustainability transitions, more attention for policy theories has been argued for (Kern and Rogge, 2018). Since actors can have a considerable influence on institutional shifts in renewable energy transitions (Bohnsack et al., 2016; Galeano Galvan et al., 2020), it is important to include the perspectives of actors involved in transitions in analyzing this policy challenge. In this paper, the actor-centered institutionalism (ACI) framework (Scharpf, 1997) is used to analyze the policy challenge of resource-efficiency in solar PV.

ACI can help explain perceptions regarding a problem and preferences for policy solutions and outcomes of different stakeholders regarding a policy challenge. It also indicates potential conflicts between these different perceptions and preferences. This approach results in a conceptual scheme that enables us to analyze the capacity of given systems of policy interactions for dealing with certain policy problems, in this case the transition to resource-efficiency in solar PV (Scharpf, 1997). The framework has been used to analyze diverse fields, ranging from agricultural policy reform (Coleman, 2001), energy policy (Kriesi & Jegen, 2001) and renewable energy trade (Hughes and Meckling, 2016), to climate adaptation of railway systems (Rotter et al., 2016) and forest management (Sonnhof et al., 2021). The ACI framework has been combined with other frameworks in the past, e.g., with network analysis (Kriesi and Jegen, 2001) or the Advocacy Coalition Framework (Hughes and Meckling, 2016). The framework will be further operationalized in Section 3.2. The framing of environmental issues like this one has been closely connected to scientific knowledge in the past decades and scientific actors are assumed to be rather influential in the policy process (Wesselink et al., 2013), which makes it relevant to additionally consider the science-policy interface framework. We are not aware of any work that combines the ACI framework with science-policy interface literature.

The science-policy interface facilitates the exchange and joint construction of knowledge, that can be of use in enhancing the policy-making process (Sokolovska, 2019). This interface has been discussed extensively in the literature (Sokolovska et al., 2019; Sundqvist et al., 2018; Turnhout et al., 2016). In the past, science and policy were considered as clearly separated from each other. They were believed to *'represent two different subsystems with different 'inner logics, 'goals', and 'rules'. Science is constantly searching for the truth and politics seek to win and preserve power'* (Sokolovska, 2019, p. 2). This difference is endorsed by Sundqvist et al. (2018), who argue that science and policy can be considered two different worlds, with different functions and understandings.

In our modern-day societies, however, science and policy are increasingly intertwined (Sundqvist et al., 2018; Sokolovska et al., 2019). According to Turnhout et al. (2016), a 'one world' approach to science and policy is necessary since research can only be policy relevant if knowledge and problem framings correspond with each other. The audience for which the research is aimed should consider the scientific results useful for them to be of value (Turnhout et al., 2016). Therefore, the focus is on finding a way of communication between different scientific, societal and governmental actors, without weakening the quality of the knowledge (Sokolovska et al., 2019).

Following this logic, scientific and policy actors should have corresponding orientations with matching preferences and perceptions or have the institutional capabilities to look for common grounds. Only then they can provide quality knowledge and solve policy challenges. These actors encounter each other in actor constellations, which are complex arenas with multiple interactions, interrelations and interdependencies (Scharpf, 1997). The ACI framework can be a helpful tool in analyzing whether science and policy actors are aligned and integrated in practice and, thus, able address policy challenges effectively, or whether conflicts may emerge.

The importance of science in policymaking in the case of solar PV is acknowledged by Valero et al. (2018), who emphasize that a good understanding of what critical materials are present in solar PV is necessary to develop effective recycling policies. Other authors go even further by explicitly proposing measures or regulations to increase recycling practices, such as making manufacturers responsible for recovering materials from end-of-life solar PV (Chowdhury et al., 2020). Anctil and Fthenakis (2013) also directly address policymakers by stating that the cost of photovoltaics should include end-of-life options and mentioning the possibility of making manufacturers responsible for end-of-life solar PV. This shows these scientists do not aspire to be neutral, but they take a clear stance in the debate. This corresponds with the argument of Wesselink et al. (2013, p. 3) on the neutrality of science in environmental governance: '*environmental discourses are not neutral descriptions of a real world out there, but are in practice based on human, and thus political or partial interpretations of technical knowledge by powerful interests'*. This argument is supported by Turnhout et al. (2016), who argue that knowledge is not and should not be a neutral contribution to policy. According to them, being policy relevant is to be policy prescriptive. Scientists are therefore expected to have distinct preferences regarding resource-efficiency policies in solar PV, thus influencing the policy landscape. Applying the ACI framework to the policy challenge of increasing resource-efficiency in solar PV will demonstrate whether the influence of science is actually prevalent in the solar PV policy landscape, to what extent other actors' perceptions and preferences play a role, how the different involved actors relate to each other and whether their goals and logics are aligned.

3. Methods

ACI was developed to explain past policy choices, resulting in systematic knowledge that, in turn, can be re-used for developing policy recommendations (Scharpf, 1997). The framework facilitates a conceptual scheme we can use for analyzing the capacity of given policy systems for dealing with certain policy problems, such as the challenge of innovation in solar PV. The analysis is applied to the solar PV sector of the Netherlands as a case, within an EU policy context. Since policies and regulations regarding this topic are mainly established at EU level, the results will mostly be applicable to other EU member states as well.

Table 1
The analyzed policy documents.

Document title	Document type	Source	Publication year
EU documents			
EU Waste Framework Directive	Regulation	European Commission	2008
EU Ecodesign Directive	Regulation	European Commission	2009
EU Roadmap to a Resource Efficient Europe	Policy vision	European Commission	2011
EU WEEE Directive	Regulation	European Commission	2012
EU Guidance on EPR Report	Report	European Commission	2014
EU Renewable Energy Directive	Regulation	European Commission	2018
EU Green Deal	Action Plan	European Commission	2019
EU Circular Economy Action Plan	Action Plan	European Commission	2020
EU Preparatory study for solar PV	Report	European Commission Joint Research Centre	2020
Dutch documents			
Nederland Circulair in 2050	Policy vision	Dutch Ministry of Infrastructure & Water quality	2016
Grondstoffenakkoord	Intention agreement	Dutch Ministry of Infrastructure & Water quality	2017
Transitieagenda Maakindustrie	Action Plan	Dutch Ministry of Infrastructure & Water quality	2018
Uitvoeringsprogramma Circulaire Economie 2020-2023	Action Plan	Dutch Ministry of Infrastructure & Water quality	2020

3.1. *Policy analysis*

First, a substantive policy analysis regarding resource-efficiency in solar PV was conducted, of policies on both the Dutch and EU level. This analysis illustrates the current policy landscape in which the involved stakeholders operate, and thus provides a contextual background to the actor analysis. To analyze the transition to more resource-efficient solar PV in the future, an illustration of the status quo of the relevant policies is required (Scharpf, 1997).

Documents were collected through a snowball sampling method (Bryman, 2016, p. 415), with the 'EU WEEE Directive' (Directive 2012/19/EU) as a starting point for the EU documents, and 'Nederland Circulair in 2050' (2016) as a starting point for the Dutch documents (Table 1). The documents go back to the 'Waste Framework Directive' (2008) and the 'Nederland Circulair in 2050' (2016) document, since these are the first documents that establish circular economy principles in policy in the EU and the Netherlands respectively. The documents were analyzed with the help of an inductive coding process (Bryman, 2016) (see Appendix A and B). This provides an overview of the status quo of the policy landscape, as can be found in Section 4.1.

3.2. *Actor analysis*

Subsequently, the different policy perceptions and preferences of the involved actors regarding resource-efficiency and solar PV policy were mapped with the help of qualitative interviews. This resulted in an overview of the gap between the preferences of the involved actors and the policy outcomes that are to be reached. This overview provides insight into whether the current policy landscape can deal with the challenge of circularity in solar PV effectively and appropriately, and enables the formulation of policy recommendations (Scharpf, 1997).

According to Scharpf (1997), actors dealing with policy problems hold different *perceptions* of problems, which include both problem definitions and underlying cause-effect hypotheses. They also possess certain, more operational substantive, *capabilities*, such as resources, information and technologies. And finally, actors have *preferences* concerning the policy options and outcomes. Altogether, we operationalized these three elements as follows:

- *Perceptions*: rather abstract, high-level understandings of actors regarding the policy problem, underlying cause-effect relationships, which matters are considered important, and which are not.
- *Preferences*: more concrete policy solutions that should be taken to address the policy challenge, according to the involved actors.
- *Capabilities*: what can be done to reach these policy solutions.

In Scharpf's framework, the involved actors bring these perceptions, preferences and capabilities into the policy arena, and together form so called actor constellations. These actor constellations reflect temporary positions in the policy making game. These constellations may be confrontational or cooperative and can evolve over time. They illustrate the degree to which the aspirations of the involved actors are compatible with each other, and therefore describe the level of potential conflict. Through interactions, and strategic behavior within these constellations, different policy options are communicated, exchanged, negotiated and compromised (Scharpf, 1997). This process is constrained and enabled by institutional settings, such as bureaucratic organizations, and institutional rules, such as legal provisions, EU directives and cultural norms. These institutional settings and rules are easy to distinguish, and therefore Scharpf (1997, p. 39) highlights that researchers also have access to the actor's perceptions, preferences and capabilities.

Additionally, the institutional context also accounts for the limited number of respondents that is needed for an actor analysis. Similar actors operate in the same institutional settings and constellations, and as such, they are assumed to have corresponding orientations and understandings. The orientations of one actor therefore are presumed to represent the beliefs and preferences of similar actors (Scharpf, 1997). 12 semi-structured interviews and 1 e-mail interview (R12) were conducted to collect the data for the actor analysis (Bryman, 2016). An overview of the respondents can be found in Table 2 and the interview topic list can be found in

Table 2
The interviewed respondents.

Respondent number	Actor group	Organization
R1	Governmental actor	Innovation supporting organization
R2	Governmental actor	Province
R3	Scientific actor	Knowledge institute
R4	Governmental actor	Ministry
R5	Governmental actor	Ministry
R6	Producing actor	Interest group of traditional silicon PV producers
R7	Producing actor	Circular producer start-up
R8	End-of-life actor	Repairing and refurbishing start-up
R9	Technology developing actor	International R&D institute
R10	Scientific actor	University
R11	Technology developing actor	International R&D institute
R12	End-of-life actor	European recycling organization
R13	Technology developing actor	Emerging technology developer

Table 3
Notions indicating the actors' priorities regarding the policy problem.

	Indicating notions
Low priority	*Not important; unimportant; insignificant; minor interest; no priority; of no value; no attention; unnecessary; no action; not an issue;*
Medium priority	*Not the most important; should receive attention, but not immediate; other matters are more pressing; relatively less urgent*
High priority	*Very important; a lot of attention; crucial; essential; necessary; relevant; urgent; major interest; large problem; immediate action*

Table 4
Notions indicating the actors' preferences regarding policy solutions.

	Indicating notions
Negative preference	*Not suitable; unfit; inappropriate; improper; unusable; inefficient; unfitting; ineffective; inaccurate; incorrect; insignificant; of no value; no attention; unnecessary;*
Neutral preference	*Indifferent; neutral; undecided; no opinion; not clear; not mentioned*
Positive preference	*Very suitable; fitting; appropriate; proper; usable; efficient; effective; accurate; significant; of great value; relevant; necessary*

Appendix C. Transcriptions of the interviews are, due to respondent anonymity, available on request.

The interview transcriptions were analyzed through a deductive coding process, based on ACI. The data were thus coded for the *perceptions* of the problem, the policy *preferences* defined in the various actor constellations, and the *capabilities* to influence policy outcomes of the different actors. An overview of the codebook can be found in Appendix D, and a coding example can be found in Appendix E. Interpretation of the results for *perceptions* was done making use of the categories "low", "medium", and "high" priority, to highlight the perceptions and priorities the involved actors have regarding the policy problem. The scaling of the respondents' answers into these categories was made on the basis of word choice, notions and concepts (Table 3).

The interpretation of the results for *preferences* was done making use of the categories "positive preference", "neutral preference" and "negative preference", to illustrate the different policy solutions following from the actor constellations. Again, the scaling of preferences into these categories was made based on word choice, notions and concepts (Table 4).

For the *capabilities* part, it was examined what resources the involved actors believe to be necessary to address the challenge of resource-efficiency in PV, and what capabilities they have to influence their preferred policy solutions. Possible resources are, among others, human and social capital, money, technological capabilities and access to information (Scharpf, 1997, p. 43). From the interviews, the role of government appeared to be crucial in enhancing the capabilities of the involved actors for dealing with the challenge of resource-efficiency in PV. Therefore, the interpretation of results regarding *capabilities* was done by illustrating the particular role government should take up according to the involved actors. The actors' priorities regarding the possible government roles were illustrated making use of the categories "low", "medium" and "high" priority again (Table 3).

4. Results

4.1. Policy analysis

4.1.1. EU policy analysis

The need for resource-efficiency is clearly acknowledged within EU policy (see Fig. 1)(European Commission, 2019, 2020, 2008, 2020b). Environmental reasons (Green Deal), dependency reasons (00 and economic reasons (Roadmap to a Resource Efficient Europe; Circular Economy Action Plan) are recognized as drivers for this need. A shift is taking place from a linear to a circular economy, with waste as a resource, attention for 'reduce, reuse, recycle' (European Commission, 2008), Ecodesign efforts (European Commission, 2009), and Extended Producer Responsibility (EPR) principles (European Commission, 2008; Monier et al., 2014).

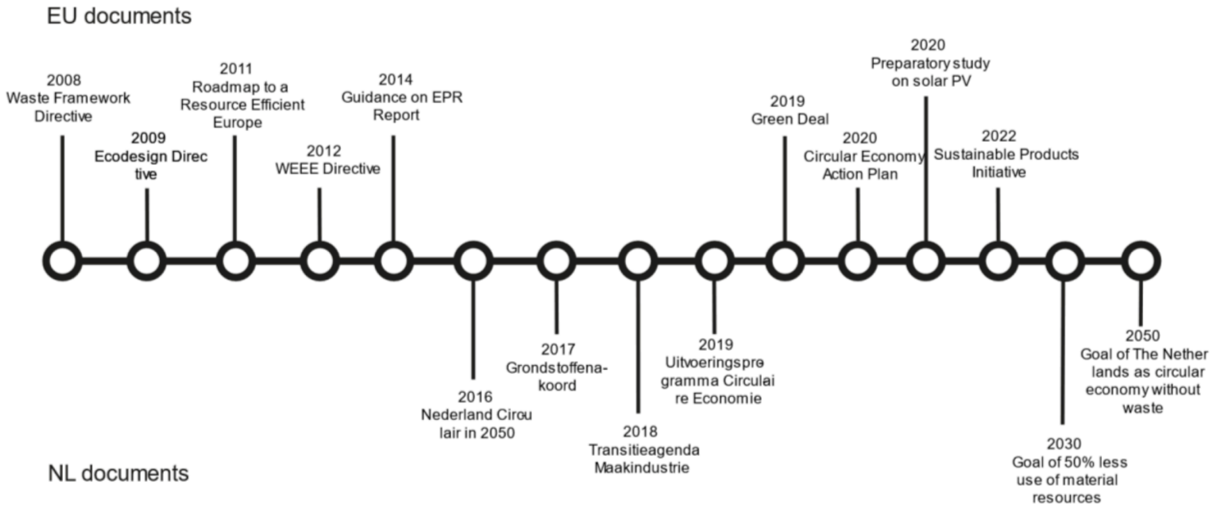

Fig. 1. Timeline of both EU and Dutch policy documents related to resource-efficiency and solar PV.

The requirements for the sustainable design of products, set in the Ecodesign Directive (European Commission, 2009) do not specifically apply to solar PV panels yet, which does not incentivize a sustainable design of emerging solar PV technologies. Moverover, according to the EU Waste Electrical and Electronic Equipment (WEEE) Directive, which is the key policy regulating the collection and recycling of PV waste in the EU, from 2018 onwards a minimum of 85% of e-waste shall be recovered, and 80% shall be prepared for re-use and recycle (European Commission, 2012) This percentage is based on the collected weight for the total category, not on the weight of separate products or materials. As a consequence, the heavy, easy to recycle materials are re-used or recycled, while the incentive to recycle lighter, hard to recycle critical materials is lacking (Ardente et al., 2019; Lapko et al., 2018; Ylä-Mella and Pongrácz, 2016). Also, targets for recovery and recycling of e-waste classify end-of-life solar PV in the category of '*consumer equipment and photovoltaic panels*' European Commission, 2012). This means that solar panels are collected together with other electronic equipment, so their specificities cannot be taken into account sufficiently. At the same time, more far-reaching and specified EU policies have been researched (Dodd et al., 2020) and are currently being developed (e.g. EU Sustainable Products Initiative, (European Commission 2022) that will also be applicable to the case of solar PV. Measures like extended ecodesign requirements for PV modules, Energy Labelling criteria, Ecolabelling criteria, and Green Public Procurement criteria might be anchored in regulations in the future, in this way stimulating resource-efficiency in solar PV (Dodd et al., 2020).

The current situation may therefore be different if the European Commission's Sustainable Products Initiative (European Commission, 2022) will be implemented in a few years. How the current policies and directives come into practice in member states' policy can be illustrated by the case of the Netherlands, described in section 4.1.2.

4.1.2. *Dutch policy analysis*

Like it is for the EU, achieving a circular economy is also a goal for the Dutch government (Nederland Circulair in 2050). In this prospective circular economy, the importance of renewable energy technologies is recognized. While the EU policies seem to be too general to take specific technologies into account, the Dutch policies do so more specifically. Achieving a fully circular economy by 2050, safeguarding critical raw material supply and increased resource-efficiency are set as objectives (Nederland Circulair in 2050; Uitvoeringsprogramme Circulaire Economie 2020–2023; Transitie-agenda Maakindustrie). Regulations, collaborations and research and innovation are required to achieve these circular economy goals (Nederland Circulair in 2050; Grondstoffenakkoord; Uitvoeringsprogramme Circulaire Economie 2020–2023; Transitie-agenda Maakindustrie). Research and innovation projects and investments are established to support circularity in solar PV (Uitvoeringsprogramma Circulaire Economie 2020-2023) and a technological roadmap is being developed for optimizing recycling of critical raw materials (Transitie-agenda Maakindustrie).

4.2. *Actor analysis*

This section shows how the different involved actors perceive the existing policy landscape as described in Section 4.1. First the actors' perceptions of the problem and their preferences regarding possible policy solutions will be explored (Section 4.2.1. and 4.2.2.), followed by the capabilities they believe the government should have to influence the policy process (Section 4.2.3.) (Scharpf, 1997).

4.2.1. *Perceptions*

Perceptions on circularity: Attention for circular solar panels is currently centered among scientific actors or a few solar PV producers who want to distinguish themselves from the mainstream producers (R1, R2, R7). On the regular market, the cheapest price wins (R4, R5). Moreover, the majority of manufacturers believe that recycling percentages, based on mass, are very high for solar panels and therefore circularity is not an issue (R6). Technological possibilities do not seem to be the problem for increasing circularity; the issue is

Table 5

An indication of the actors' perceptions regarding increasing resource-efficiency and accelerating the energy transition.

Issue	Low priority	Medium priority	High priority
Increasing resource-efficiency in solar PV	R6	R1, R2, R3, R4, R5, R10, R11, R13	R7, R8, R9, R12
Accelerating the energy transition			R1, R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R12, R13

their affordability (R7). According to technology developers, everyone would prefer to increase circularity as long as it is cost effective (R9). Circular producers believe it is financially competitive on the long term since materials can be re-used and recycled while maintaining high value (R7), but the majority of producers do not see a business case yet (R6). This is endorsed by end-of-life actors, who state PV waste currently results from panels broken due to incidents or bad handling instead of large volumes of end-of-life panels (R12). However, when these volumes increase, a viable business case is expected to emerge (R6, R12). A further dilemma is indicated by technology developers: Increasing durability of a product often increases recycling difficulty at the same time (R9).

Additionally, technological lock-in in industrial production processes and societal lock-in of certain products are considered reasons for circularity limitations (R4, R5, R6). Changes cannot be too radical according to the producers, because production processes are already established and altering them is very complicated. Therefore, innovations need to fit in the current processes to be feasible. However, technology developers state there are possibilities for changes while taking the problem of lock-in into account, such as implementing silicon/perovskite tandem cells that can be produced through manufacturing processes that are relatively similar to those of silicon-based solar PV (R9).

Perceptions on emerging solar PV technologies: This technological lock-in of traditional solar PV seems to result in limited awareness for emerging solar PV technologies. Attention for these technologies currently seems to be centered among technology developers (R9, R11) and scientists (R10). They believe these technologies can play a large role in the energy transition, due to their high efficiencies, low producing costs, low electricity costs and improved environmental impacts. Silicon-based solar cells will be dominant till around 2030, but after that thin film/silicon tandem cells are expected to take up an important role (R9). In order to supply the energy demand in the future, the energy yield of renewable energy sources needs to increase. Silicon cells are reaching their fundamental limits, so emerging technologies provide a solution (R9, R10, R11). Silicon-based solar cells should still be deployed as much as possible to accelerate the energy transition but research into emerging technologies should be conducted since these will be even better in the future (R10, R11).

By the majority of other actors, emerging solar PV technologies are not considered yet. Mainstream producers believe there is no time available to develop emerging solar PV technologies. Instead, they think we should focus on implementing traditional silicon-based solar PV as much as possible, since these are proven technologies and can contribute to the energy transition (R6). End-of-life actors do logically not take emerging technologies into account yet, because of their early development stage (R8, R12).

Perceptions on sustainability: According to governmental actors, developers and producers have to feel responsible for doing good to the environment (R4, R5). This stance is shared by scientific actors, who highlight the value of safe-by-design practices (R3). Technology developing actors believe the mentality is already changing towards more sense of responsibility (R9, R11). Attention is shifting to developing products with higher quality, longer durability, and lower environmental pressures, and environmental impact assessments are included from the beginning of every research process (R9, R11). At the same time, they emphasize policy makers should also have a feeling of responsibility for increased sustainability in solar PV. Circularity and innovation in PV should be supported through adequate policies and R&D projects and technologies and policies should evolve side-by-side (R9).

Moreover, scientific actors emphasize a comprehensive view on environmental pressures is necessary. Instead of just focusing on climate change toxicity, material use and circularity should receive attention as well (R3). End-of-life actors share this stance, indicating that the amount of toxic chemicals in solar panels should be limited. This would result in lower risks for the environment when dealing with damaged or end-of-life solar panels (R8). Governmental actors state that it is not just about circularity, but about products with less impact on the environment than before. Just focusing on circular technologies may lead to problem-shifting (R4, R5). According to scientists, all different trade-offs and factors should be taken into account to come to policy decisions with the best possible outcomes (R3). This is endorsed by technology developers, who emphasize that new technologies should always be considered comprehensively, from both economic and environmental perspectives (R9, R11).

Attention for circularity constraints energy transition: All involved actors acknowledge the importance of accelerating the energy transition. At the same time some actors believe increased attention for circularity in solar PV would delay the energy transition, and therefore do not consider it a priority (Table 5). A delay of the energy transition as a consequence of increased attention for circularity would result in more harmful impacts than the benefits of circularity entail, according to them (R1, R6). Other actors believe circularity should be taken into account (R2, R3, R8, R10). Things like environmental impacts, safety during use and circularity at the end-of-life of solar PV should be considered in the development stage already to prevent problem-shifting in the future (R3, R4, R5, R11). The importance of safe- and circular-by-design is endorsed by the few circular producers (R7), who consider circularity as their unique selling point. Although all actors acknowledge the importance of accelerating the energy transition, awareness of the potential of increasing resource-efficiency and emerging solar PV technologies seems lacking among the mainstream actors. This is remarkable since these technologies are expected to play a large role in the future, according to scientists and technology developers (R9, R10, R11).

4.2.2. *Preferences for policy solutions*

Striking a balance between innovation and new technologies versus security and control: Increased insight into the energy intensity or material use associated with solar PV production processes is necessary to steer them towards more circularity and sustainability, according to governmental actors and scientists (R1, R3). This can be reached through an ecolabel, which is considered a first step in a

Table 6
An indication of the actors' preferences regarding setting strict criteria, stimulating innovation, safety and security and the implementation of new and emerging technologies. A '+' indicates a positive preference, a '0' neutral preference, '-' negative preference.

	Setting strict criteria	Stimulating innovation	Safety and security	Implementation of new technologies
R1, R2, R7, R8, R12	+	-	0	0
R3	+	-	+	-
R4, R5, R6	0	0	+	-
R9	0	0	-	+
R10, R11, R13	-	+	-	+

larger transition process (R4, R5). Besides enhanced information, strict criteria are considered crucial in increasing circularity and sustainability in solar PV. To facilitate circularity the existing criteria for recycling based on mass could be replaced by criteria based on criticality or value of materials (R3, R7), since the current recycling criteria do not stimulate recycling actors to recover more than glass and aluminum (R9). Moreover, scientific and end-of-life actors believe demands could be set for the longevity of use of solar panels. This could prevent the replacement of well-functioning solar panels, as soon as more efficient panels enter the market. At the same time, reuse of panels could be encouraged by setting criteria (R3, R8, R12).

These criteria could also facilitate sustainable innovation in general, according to some. Far-reaching ambitions and regulations could help in stimulating producers to adapt their products. It is believed that if, for instance, lead-containing panels were banned from the market now, we would have lead-free panels for similar prices in a few years (R1). This view on setting criteria is shared by some scientific actors, who state that criteria are of great value in increasing sustainability and circularity (R3). However, technology developers warn these criteria can also threaten innovation, by excluding certain materials or potential impacts beforehand (R11). Certain materials, although allegedly dangerous to human health or the environment, can be an essential part of a new, improved technology after thorough research. If innovations can provide benefits in other ways, e.g. efficiency or economic benefits, we might have to accept a certain level of risk.

The potential of emerging solar PV technologies, such as perovskites or tandem cells, is acknowledged by technology developers, scientists and a few governmental actors (R1, R9, R10, R11). However, the majority of producers emphasize silicon-based solar panels account for around 90% of the market share and are therefore locked-in (R6). Simultaneously, some actors state emerging technologies need to be researched more extensively before they can be implemented on a large scale, for safety reasons (R3, R4, R5). These actors want to be completely sure changes from the status quo are better and necessary, before implementing these novelties. Since emerging technologies have been researched for approximately a decade only, absolute safety and security cannot be guaranteed in all cases. Therefore their implementation is not yet seen as a serious option on the short term (R6). However, technology developers and some scientists emphasize that a certain level of risk needs to be accepted (R9, R10, R11). Simultaneously, according to technology developers lock-in does not necessarily have to be a problem since the manufacturing processes can be adapted in such a way they are similar to those of silicon-based solar panels (R9). Safety and security seems to be given priority over implementing new, promising technologies, at least by governmental actors, some scientists and producers. An overview of the actors' preferences can be found in Table 6.

Solar PV production processes currently being located in China is considered precarious by most actors, since it makes transparency about energy and material use in the value chain difficult. Relocating solar PV production to Europe could result in increasing transparency and improved circularity, according to multiple actors (R6, R8, R9. R10, R11). Technology developers believe Europe has everything to support the PV value chain, and they emphasize the economic opportunities a European PV industry could bring (R11). However, policies and regulations to stimulate relocating this chain to Europe have to be developed (R9). At the same time, emerging solar PV technologies provide opportunities for establishing a European PV value chain, since these technologies are mainly being developed in Europe (R9, R11).

4.2.3. Capabilities

A leading or facilitating government?: The involved actors distinguished several capabilities they consider essential in dealing with the challenge of resource-efficiency in solar PV. They referred to material resources, e.g. innovation subsidies, but also to increased access to information, through knowledge networks and establishing relations between the different actors. All actors emphasize the significance of the role of government, both on the EU as well as the national level, in developing and expanding their capabilities in dealing with this challenge. Therefore, in this paper we specifically focus on the capabilities of governmental actors. However, the actors indicate different priorities regarding the government's role in further stimulating these capabilities (Table 7). According to governmental actors (R2, R4, R5), government should take up a coordinating, facilitating and accelerating role. Governments can facilitate innovation by bringing different parties together and create innovation stimulating policies, such as subsidies for developers of circular solar panels (R2, R1). Knowledge networks, facilitated by the government, can help in uniting involved stakeholders and as a consequence lead to accelerating developments. Furthermore, government facilitates research and development, by commanding certain research at knowledge institutes, e.g. about environmental impacts or repairability of certain products. Scientific actors emphasize the importance of decision-making based on solid knowledge. The main goal is to set the value chain parties in motion towards a different way of working, taking the environment into account more.

The Extended Producer Responsibility (EPR) and Ecodesign principles are used by governments to create a feeling of responsibility among producers. However, the EPR system currently does not lead to a feeling of responsibility because of the large distance between the beginning and the end of the value chain (R4, R5). Policy aimed at eco-design such as the EU Ecodesign Directive is perceived as

Table 7
An indication of the actors' positions regarding the role of government. A '+' indicates a positive preference, a '0' neutral preference, '-' negative preference.

	Leading role for government (e.g. ecodesign policies)	Facilitating role for government (e.g. network building)
R1, R2, R4, R5, R6	-	+
R3, R8, R10, R11, R13	0	0
R7, R9, R12	+	-

effective (R1, R4, R5, R9, R11, R12). This suggests a more leading role for government, in which clear goals are set for developers, producers and manufacturers. The value of this regulating task is emphasized by technology developers, scientists and end-of-life actors, who state that when certain standards are set, e.g. related to environmental impacts or materials intensity, the market is set in motion and technology will follow (R9, R10, R11, R12). These standards should not be too strict or premature, to safeguard innovation potential (R11, R13).

5. Discussion

In Section 4, the Dutch and EU policies related to resource-efficiency in solar PV were analyzed to provide an overview of the policy landscape the different involved actors operate in. It became clear there is considerable attention for resource-efficiency in both the Dutch and the EU policies, although most remain rather general and cannot be specifically applied to solar PV. In the future this may change due to the Sustainable Products Initiative that is currently being developed. Moreover, the perceptions, preferences and capabilities regarding resource-efficiency in solar PV of the different involved stakeholders were discussed.

Following Scharpf's ACI (Scharpf, 1997), these different varying perceptions and preferences lead to conflicts emerging from the different actor constellations, in which the feasible courses of action that the actors could take are illustrated. The strategies of the different actors in the constellations might be compatible with each other but might also lead to potential conflicts if they do not align. For example, regarding accelerating the energy transition and increasing circularity (Section 4.2.1.), conflict over accelerating the energy transition is not expected, since all actors agree on the importance of that; yet, dispute about increasing circularity is likely to arise.

To be able to address these conflicts effectively, they should be made explicit (Sarkki et al, 2014), as this paper contributes to. This is endorsed by Scharpf Scharpf (1997), emphasizing empirical information is a prerequisite for finding potential solutions with the help of the ACI. Moreover, an adaptable science-policy interface is required, since conflicts and trade-offs are unavoidable and universally ideal options to deal with them are lacking (Sarkki et al., 2014). The possible modes of interaction through which the different potential conflicts are to be resolved could be a subject of further research. However, Section 4.2.3. already explores the preferences for a mode of interaction according to the different actors. Some actors prefer a facilitating role for government, likely relying on *negotiation* as a mode of interaction ((Scharpf, 1997, p. 195-215) . Other actors prioritize a leading role for government, corresponding with the mode of interaction *hierarchical direction* (Scharpf, 1997, p. 171-193).

When applying the science-policy interface literature to this policy challenge, improved alignment between scientific and policy actors is considered necessary to adjust the actor constellations and create better outcomes. Science and policy are increasingly integrated in our present society (Sundqvist et al., 2018; Sokolovska et al., 2019). In the case of solar PV, however, they seem to diverge regarding some issues, presumably due to the different aims the actors have. The aim of scientists and technology developers is to innovate, while the aim of policy makers is to avoid risks and search for verification (Hoppe, 2005). Aligning these aims would result in reduced levels of potential conflict in the different actor constellations.

Since science and policy are co-dependent in most western societies (Sokolovska et al., 2019), improving alignment and consequently reducing the potential level of conflict seems inevitable to achieve effective and appropriate policy solutions. This mutual dependency can be recognized in practice concerning the case of solar PV. Policymakers depend on science for providing information about risks, but also for knowledge about innovations such as emerging solar PV technologies. At the same time science depends on public regulatory power, to establish policies and regulations that support the implementations of these innovations. The case of resource-efficiency in solar PV is a clear illustration of this mutual dependency. Extensive research and development take place, but for these innovations to actually be implemented at a large scale the policy landscape needs to be adapted, according to the different involved actors. Turnhout et al. (2016) and Hukkinen (2020) state that the role of scientific knowledge is performative for policy, claiming scientific results constitute reality. In the current policy landscape, it rather appears to be the other way around: the policy landscape seems to maintain a techno-institutional lock-in (Unruh, 2000) of traditional, silicon-based solar PV. Even though research and development are focusing on circular solar panels or emerging solar PV technologies and scientists and technology developers emphasize the potential and importance of these innovations, most involved actors and the policy process do not seem to incorporate this stance. After all, replacing a whole system requires radical, far-reaching change, which is difficult to accomplish (Unruh, 2002). This corresponds with the analyses of Kirshner et al. (2019) and Strauch (2020), who find that solar PV has developed from niche to regime. This lock-in of traditional solar PV could be overcome by adjusting the actor constellations towards more alignment between the different involved science and policy actors.

Lock-in is often seen as negative, leading to the use of inferior technologies instead of new, improved options (Dosi and Nelson, 1994). At the same time, this lock-in and the positive feedback mechanisms that it entails might also be beneficial to the implementation of emerging solar PV technologies. Existing techno-institutional systems also lead to stability and reliability in the system. A slower paced '*continuity*' approach – modifying particular parts or components of the system while maintaining the overall system structure – often works better in achieving effective change (Unruh, 2002). An example of such continuity in the case of solar PV would be implementing tandem cell technologies. Tandem cells, combining perovskite or possibly III-V solar cells with silicon-based solar cells, form a feasible alternative to traditional cells, providing high efficiencies with moderate additional costs. The lock-in of the existing techno-institutional system surrounding silicon-based solar panels can be used to the advantage of the implementation of these tandem cells (Strauch, 2020). Since there currently is a locked-in system they can be integrated into relatively easily, these tandem cells do not have to work their way from niche markets into the mainstream technology paradigms. While a *continuity* approach often leads to less favorable performance or efficiency outcomes compared to radical paradigm changes (Unruh, 2002), silicon-based tandem cells perform better than many other emerging solar PV technologies (Wilson et al., 2020). Modifying a selected part of the existing system is thus easier to accomplish and might lead to comparable or even superior results in this case.

Having said that, modifying the system is influenced by different actors, each with their own interests and powers. Avelino and Wittmayer (2015) emphasize the need to explicitly consider the influence of power in transitions. In most cases the coalition of policymakers and incumbent firms is most powerful, and thus determines the socio-technical regime, i.e. '*the locus of established practices and associated rules that enable and constrain incumbent actors in relation to existing systems*' (Geels, 2014, p. 23). This also includes the complex of scientific knowledges, technological practices and infrastructures (Kemp et al., 1998). This powerful position of policymakers and incumbent firms logically follows from the state-market logic that has been dominating western societies in the past decades (Avelino and Wittmayer, 2015). This dominant position of the state and the market is also implied by our analysis, indicating the 'regime' consists of the government and mainstream producers, having a focus on traditional, silicon-based solar PV with limited attention for resource-efficiency or emerging technologies. These findings are confirmed by Kirshner et al. (2019), who argue solar PV has become a regime itself, and Strauch (2020) who describes the dominance of silicon-based solar PV in the existing regime. According to Lindberg and Kammermann (2021), the regime of renewable energy industry actors is characterized by a strong faith in markets, which corresponds with the findings in this paper. The 'niche' actors, such as the circular producers or technology developers, are aiming at breaking through this regime (Avelino and Wittmayer, 2015; Geels, 2014).

They seem to succeed partially, since resource-efficiency goals are established in policies and funding is allocated towards research and development projects. However, real breakthroughs cannot yet be distinguished, which implies the niche actors are not yet powerful enough to establish radical innovation (Geels, 2002). Our analysis shows that the governmental actors, although able to impose rules and regulations and thus having the most institutional power, do not choose to use their power by taking up a strong and leading role. Rather, they prefer taking up a facilitating role, which sounds neutral but '*in effect means that the government privileges powerful regime actors with more capabilities, financial resources and market positions*' (Geels, 2014, p. 34). The policymakers thus exercise their 'reinforcive power' (Avelino and Wittmayer, 2015), thereby acting as guardian of the status quo. Niche actors, in this case the stakeholders in favor of increased resource-efficiency, will have to exercise their innovative and transformative power and influence the governmental actors adequately (Avelino and Wittmayer, 2015), forcing them to act beyond merely stating ambitions and thus changing regime configurations (Lindberg and Kammermann, 2021). The science-policy interface could function as an arena for these niche actors to influence the regime (Diaz et al., 2013) and act as a 'boundary spanner' (Smink et al., 2015), hence possibly establishing a new paradigm of resource-efficiency in solar PV. How these niche actors could influence the regime, what support they would need to adequately do so and how the regime would react to this could be a subject of further research.

6. Conclusions

This paper provided an overview of the required transition towards more resource-efficiency in solar PV, and showed how the actors involved navigate this transition within the existing policy landscape. Altogether, resource-efficiency is considered important by a few stakeholders, but mainstream actors do not yet recognize its value. Existing policies, both on EU and national levels, do set resource-efficiency goals, but these are not fully accommodated to PV technologies. To actually increase resource-efficiency, a 'circular-by-design' or 'design-to-deconstruct' approach is necessary. This is especially relevant for emerging PV technologies, since these are still in an early stage of development and therefore adaptations regarding materials intensity can be made relatively easily.

At present, actors prioritizing resource-efficiency in solar PV seem to have interacted in what can be regarded as a niche space, while the regime institutionalizing around established PV technologies consists of policymakers and relatively incumbent firms, favoring traditional silicon-based solar PVs. The latter actors prefer a facilitating role for governments, which benefits the position of the already established silicon-based PV. The actors within the niche space are aiming at breaking through this relatively newly-emerged regime and seem to succeed partially based on the awareness for resource-efficiency in recent policies and technologies. However, silicon-based PV currently remains locked in within the policy landscape. This indicates a task for policymakers for being more open to scientific input and innovation in the case of solar PV. At the same time, it reveals a responsibility for the involved scientists and technology developers to address policymakers more effectively. The ACI framework shows that the perceptions and preferences of the various actors are currently insufficiently aligned, which makes it difficult to address this challenge effectively. Science, policy, and the involved stakeholders should align their logics and goals better to be able to increase resource-efficiency in solar PV.

To conclude, we propose the following policy implications:

- Ecodesign and safe-by-design criteria should be established to stimulate a 'circular-by-design' or 'design-to-deconstruct' approach in (emerging) solar PV technologies;
- Recycling standards should consider material value in addition to material weight to stimulate the recycling of critical materials;
- Partnerships, collaborations and knowledge networks should be established among policy-makers and scientists, to align their perceptions and goals;
- Both EU and national governments should be clear in how to overcome conflicts among actors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

Acknowledgments

We would like to thank two anonymous reviewers for their valuable feedback that helped greatly in improving this paper.

Appendices

Appendix A Policy documents coding process

As a first step, all relevant keywords and sentences in the different documents were highlighted. Subsequently, master-codes were established by examining the links and connections between the various keywords and sentences. Afterwards, the master-codes relating to each other were gathered under a few super-codes, displaying the larger connections found in the documents. Altogether, the coding process consisted of three different layers of analysis. The EU documents and the Dutch documents were considered separately, to account for differences in policy content. For both categories the same coding process was applied. This resulted in two different codebooks, with some overlap due to the similar contents of the policy documents (See below). Two coding examples can be found in Appendix B. Finally, these codes were interpreted and analyzed, resulting in the policy analysis as can be found in Section 4.1.

The codebooks, on the basis of an inductive approach (starting from keywords and sentences, creating master-codes, resulting in super-codes).

EU policy codebook Table A.1

Table A.1
The EU policy codebook.

Examples of keywords/sentences	*Master-codes*	*Super-codes*
Climate-neutral, reducing carbon, reducing environmental footprint, no net emissions of GHGs	Environmental reasons	The need for resource-efficiency
Limited countries with resources, dependency on other countries, dependent on China, conflicts endangering supply, geopolitical developments, access to resources, securing supply	Dependency reasons	
Negative effects on the economy, new business models, threatened supply security, resource-efficient and competitive economy, decoupling economic growth from resource use	Economic reasons	
Recycling society, optimize supply of resources, using recycled material for new equipment, sound resource management, retrieval of valuable secondary raw materials,	Waste as a resource	Circular Economy efforts
Prevention of waste, preparing for re-use, sent for recovery, recycling, reducing the use of resources, waste hierarchy, increased durability, repairability, re-usability, recyclability	Reduce, re-use, recycle	
Recyclability of products, sustainable products, products that take into account resource-efficiency and end-of-life, better design, preventive design, design phase, design for recycling	Ecodesign	
Producer responsibility, financial responsibility, paying for waste removal, organizational responsibility, collecting waste, sorting waste, preparing for recycling, managing the waste, collecting end-of-life products, prepare for recycling, creating incentives for waste prevention, stimulate reuse and recycling, stimulate resource-efficiency, producers pay	Extended Producer Responsibility	

Dutch policy codebook Table A.2

Table A.2
The Dutch policy codebook.

Examples of keywords/sentences	*Master-codes*	*Super-codes*
Climate-neutral, reducing carbon, reducing environmental footprint, no net emissions of GHGs	Environmental reasons	The need for a circular economy
Limited countries with resources, dependency on other countries, dependent on China, conflicts endangering supply, geopolitical developments, access to resources, securing supply	Dependency reasons	
Negative effects on the economy, new business models, threatened supply security, resource-efficient and competitive economy, decoupling economic growth from resource use	Economic reasons	
Fully circular in 2050, less use of primary resources, shift to a circular industry, upcycling of critical materials, reducing use of resources from abroad, enhancing security of supply, increased resource-efficiency	Circular economy goals	
Laws, regulations, policy, regulatory/judicial framework, obstructive regulations, reforms, extended producer responsibility	Regulations/policies	Roadmaps to a circular future
Transcending sectors and levels, stakeholders, knowledge networks, international cooperation, agreements	Collaborations	
Innovation, circular economy research, investments, R&D, scientists, knowledge networks, designers	Research and innovation	

Appendix B Coding examples

The different coded keywords and sentences lead to the following master-codes:
Yellow: Extended producer responsibility
Green: Ecodesign
Purple: Waste as a resource
Blue: Reduce, re-use, recycle
Red: Environmental reasons
Grey: Dependency reasons
Turquoise: Economic reasons

The first for codes (yellow, green, purple and blue) can be emerged into one super-code: Circular economy efforts. The different master-codes are all related to each other, since they are all different key aspects of a circular economy.

The red, grey and turquoise master-codes together form the second super-code: ‘the need for resource-efficiency’. These three master-codes, as defined from keywords and sentences, indicate the reasons behind the EU’s aim for improved resource-efficiency and the Dutch need for a circular economy.

The examples are as follows:

Example 1: WEEE European Commission, 2012**p. 40/41).**

(20) Where appropriate, priority should be given to preparing for re-use of WEEE and its components, sub-assemblies and consumables. Where this is not preferable, all WEEE collected separately should be sent for recovery, in the course of which a high level of recycling and recovery should be achieved. In addition, producers should be encouraged to integrate recycled material in new equipment.

(21) The recovery, preparation for re-use and recycling of WEEE should be counted towards the achievement of the targets laid down in this Directive only if that recovery, preparation for re-use or recycling does not conflict with other Union or national legislation applicable to the equipment. Ensuring proper preparation for re-use, recycling and recovery of WEEE is important for sound resource management and will optimize supply of resources.

(22) Basic principles with regard to the financing of WEEE management have to be set at the level of the Union, and financing schemes have to contribute to high collection rates, as well as to the implementation of the principle of producer responsibility.

(23) Users of EEE from private households should have the possibility of returning WEEE at least free of charge. Producers should finance at least the collection from collection facilities, and the treatment, recovery and disposal of WEEE. Member States should encourage producers to take full responsibility for the WEEE collection, in particular by financing the collection of WEEE throughout the entire waste chain, including from private households, in order to avoid separately collected WEEE becoming the object of suboptimal treatment and illegal exports, to create a level playing field by harmonizing producer financing across the Union and to shift payment for the collection of this waste from general tax payers to the consumers of EEE, in line with the ‘polluter pays’ principle. In order to give maximum effect to the concept of producer responsibility, each producer should be responsible for financing the management of the waste from his own products. […] Collective schemes could provide for differentiated fees based on how easily products and the valuable secondary raw materials that they contain could be recycled.

Example 2: Circular Economy Action Plan (2020, p. 6/7)

‘*In order to make products fit for a climate-neutral, resource-efficient and circular economy, reduce waste and ensure that the performance of front-runners in sustainability progressively becomes the norm, the Commission will propose a sustainable product policy legislative initiative.*

The core of this legislative initiative will be to widen the Ecodesign Directive beyond energy-related products so as to make the Ecodesign framework applicable to the broadest possible range of products and make it deliver on circularity.

As part of this legislative initiative, and where appropriate, through complementary legislative proposals, the Commission will consider establishing sustainability principles and other appropriate ways to regulate the following aspects:

- *Improving product durability, reusability, upgradability and reparability, addressing the presence of hazardous chemicals in products, and increasing their energy and resource-efficiency.*
- *Increasing recycled content in products, while ensuring their performance and safety.*
- *Enabling remanufacturing and high-quality recycling.*
- *Reducing carbon and environmental footprints.*
- *[…]'*

Appendix C Interview topic list

The following topic list was used in the conducted semi-structured interviews, with examples of questions that were used as a guideline:

1. General

- To what extent is the need for resource-efficiency acknowledged in the solar PV sector?

2. Design phase of solar PV

- How does material intensity play a role in solar PV design?
- To what extent do emerging technologies receive attention? And to what extent are circularity/material intensity taken into account regarding emerging technologies?
- How do policy measures and regulations currently influence the design of solar PV?
- Do you think policy measures are necessary to improve the design phase of emerging solar PV? If so, what measures?

3. Usage phase of solar PV

- How does implementation of innovation in solar PV (related to circularity, resource-efficiency, emerging technologies) look like?
- How do policy measures and regulations currently influence the implementation of these innovations in solar PV?
- Do you think policy measures are necessary to stimulate innovation in solar PV? If so, what measures?

4. End-of-life phase of solar PV

- To what extent is circularity/material intensity in the end-of-life phase of solar PV accounted for in the design?
- How does this differ for traditional vs. emerging solar PV technologies?
- How do policy measures and regulations currently influence the end-of-life phase of solar PV?
- Do you think policy measures are necessary to improve the end-of-life phase? If so, what measures?

5. Stakeholder collaboration

- What stakeholders are involved in circularity of solar PV?
- How do you work together with these stakeholders?
- Do you think there are relevant stakeholders that are not involved in collaborations? If so, what kind of stakeholders?

Appendix D Codebook actor analysis

In the following table, the codebook used to analyze the collected data for the actor analysis is pictured. The interview data were coded for the perceptions, preferences and capabilities of the involved actors.

Table D.1

Table D.1
The codebook for the actor analysis.

Codes	Indicating notions
Perceptions	Beliefs, causal theories, understandings regarding the problem, understandings regarding possible solutions, policy paradigms
Preferences	Proposed policy instruments, preferred solutions, preferred outcomes, strategies considered suitable
Capabilities	Resources, financial capital, human capital, information, legal power, decision-making power, ways to influence the policy process

Appendix E Coding example actor analysis

Below, two coding examples are given for the actor analysis. The examples were coded for:
Green: Perceptions
Yellow: Preferences
Pink: Capabilities

Example 1.

‘Right now we are shifting towards a mentality of let’s do something with higher quality, that it’s more durable. [..]If we are going to make the effort of having a ecolabel certificate for this module, there also has to be a support that the policies and investors need to be forced to invest more in those types of products. And not keep on paying for things coming from China. It should also provide the criteria to investors, to say please invest more into those types of products and not put your money in things that further damage our environment. [..] When ecodesign, ecolabelling criteria will be in place, things will change even more. [..] So if at the regulatory level, they will be obliged to recover more material, then technology will also evolve in order to make those processes which are ongoing right now more cost-effective. Because that’s how the market evolves. ’

Example 2.

‘The point here is that in overall, the energies are placed to bring PV manufacturing to Europe. We have everything in Europe to support the PV value chain. But then there is the side of the policies, which should support this. How will the policies enhance this transfer of let’s manufacture everything in China or Asia to Europe? I don’t know, it’s not only about visibility but also giving more advantages to local production. This has to come from the policy level. There is a lot of lobbying going on, through Solar Power Europe for instance, and there has been good advance on the policy side. For instance, PV was not part of the Green Deal, and after a coalition that we actually started with many many knowledgeable key players of the PV value chain, went to the EU parliament and asked to reconsider what are the main pillars to be taken into account in the Green Deal.’

Furthermore, below examples of statements coded as *perceptions* are given, for the three categories low priority, medium priority and high priority, relating to increasing circularity in solar PV. After, three examples of statements coded as *preferences* are given, for the three categories negative preference, neutral preference and positive preference regarding setting strict criteria.

	Statement example
Low priority	*‘Circularity is not really an issue for us. There is no objection in the recycling; it already works perfectly fine, in our experience.’ (R6)*
Medium priority	*‘We looked at how to increase efficient material use in solar panels. But we also considered the risks of hazardous substances, and societal acceptance of panels. We think that is very important as well.’ (R3)*
High priority	*‘If, in the future, we have a fully renewable energy system, we don’t want to realize we don’t have any materials left and cannot recover materials from existing products. It’s very important to already consider this now.’ (R7)*

	Indicating notions
Negative preference	*‘If governments starts saying ‘don’t use this material, don’t use that’ because research found out that if mice eat a lot of this substance they might die.. This kills a lot of innovation, which might have turned out to be a good solution.’ (R13)*
Neutral preference	*‘When setting criteria, e.g. related to certain hazardous materials, an alternative needs to be found. Sometimes this is beneficial, but sometimes these substitutions are worse. A comprehensive view on innovation is therefore necessary.’ (R5)*
Positive preference	*‘If the EU would ban lead in solar PV now, we would have lead-free panels in three years. Things like these should definitely be enforced.’ (R2)*

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