CAN MORE PHOTOVOLTAIC WASTE SOLVE ITS OWN PARADOX?

Examining Austrian photovoltaic technology experts' evaluation of photovoltaic waste and its socio-environmental risks

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Abstract

This thesis explores the less apparent facet of photovoltaic technology—its waste. More specifically, it looks at the environmental risks that are associated with the recycling, and supply chains of this technology. Situated in the Austrian context, the country which is expanding its solar electricity production capacity and upscaling photovoltaic technology under climate-neutrality commitments, this research investigates its subject of interest through qualitative interviews with experts and key stakeholders from the Austrian solar sector. Photovoltaic waste is a new and under-researched topic in anthropology. While existing literature focuses on rural communities of the Global South and micro-practices around photovoltaic waste, I turn to the matter of concern in the context of a highly industrialized country of the Global North and examine it from the industrial perspective. I show that even in the conditions of proper recycling infrastructure and regulations, some risks remain unaddressed in the practices of photovoltaic waste treatment, challenging the underlying green principles of the technology. I argue that coupling photovoltaic waste treatment with growth principles implies economization of environmental risks which entrusts their elimination to the logic of profitability. I suggest that to create safer material infrastructure for solar power expansion, it is necessary to politicize photovoltaic waste. To develop my argument, I explore the topic from a political ecology lens and use the sociological concept of risk which means that risk cannot be reduced to technical measures alone but results from human action, social processes, and political decisions.

Key words: Photovoltaics, waste, risk, political ecology, environment, experts, technology, infrastructure

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Abbreviations

PV = Photovoltaics

kWh = Kilowatt hour (measuring unit for electricity use per hour)

kWp = Kilowatt peak (unit for forecasting electricity output of photovoltaic panels)

GW = Gigawatt (1 mln kilowatt hours)

TWh = Terawattt hours (1000 gigawatt hours)

WEEE = Waste Electrical and Electronic Equipment Directive

Introduction

Solar power is known as the emission-free, clean and renewable type of energy which is harvested directly from the sun and transformed into electricity by photovoltaic panels—one of the instrumental energy technologies in the global and especially, in the European electricity sector's low-carbon transition process. Even though solar takes up only about 3% of the global electricity share at present (iea.org, 2019) and about 10% of the European Union's total (ember-climate.org, 2021), it is the fastest growing renewable energy source on the planet alongside with wind power (irena.org, 2021).

In the European Union, solar is expanding at an unprecedented rate. Since 2019, EU-27 has added 14 terawatt-hours of solar electricity generation every year (ember-climate. org, 2021), equaling roughly 5% of the electricity that Italy consumed in 2020 (yearbook.enerdata.net, 2020). Under recently adopted the European Green Deal policy which should help Europe to reduce carbon emissions by 55% compared to 1990ies levels by the mid-century and increase renewable energy production to 40% by 2030 (ec.europa.eu, N/A), at least doubling of the current rate of annual solar expansion is required (ember-climate. org, 2021). Consequently, the European Union member states who need to meet these targets are upscaling the installment of photovoltaic technologies.

So is Austria, the EU's one of the richest economies (ec.europa.eu, 2021) where solar power expansion is underway and present in public discourse on energy transitions, or as they call it, 'Energiewende'. That one million photovoltaic panels will cover the country's rooftops in less than the next ten-year period or that Austria necessitates the construction of as many solar systems as its free spaces allow to make 2030 solar goals realistic, is the recurring topic on the news.

During my residence in Austria, the presence of solar power and photovoltaic technology in public discussions was easy to spot. Looking back, I realize that in part, this topic caught my attention due to my long-standing interest in the relations between energy, its infrastructure, and natural ecosystems. As I was already familiar with some of the socio-environmentally challenging aspects of utility-scale solar plants, and the waste of photovoltaic panels, by the time I started to follow Austria's solar shift, I became curious about local practices in dealing with discards of solar technology. For a country with the world's some of the best photovoltaic producers, extensive expertise in innovative applications of building-integrated photovoltaics (energy-innnovation-austria.at, 2017) and the intentions for solar technology rollout on its territory, management of photovoltaic waste presented itself as a critical issue for exploration.

In the existing social scientific literature, questions on solar power technologies have already been posed by scholars concerning land use, environmental, social and energy justice (Mulvaney, 2019, Mulvaney, 2014, Hornborg, 2016), economic and political ramifications of solar industry's collapse (Brock, et. al, 2020), as well as the impact of broken-down off-grid solar modules on rural communities in India and Sub-Saharan Africa (Cross & Murray, 2018, Kumar & Turner, 2020). However, studies on the experts of photovoltaic industry in highly industrialized contexts are visibly lacking, including in anthropology. My research addresses this gap and brings into focus precisely the community of experts, and links it with another less explored topic of solar waste in anthropology to ask:

1. *How do photovoltaic technology experts, and key stakeholders who are associated with the Austrian solar industry reconcile environmental risks of photovoltaic waste?*
2. *How do risks of photovoltaic waste position Austria in global relations as seen from political ecology lens and with what effects for Austria?*

I begin the thesis with an overview of Austria's present context and history of photovoltaic technology development. In chapter two, I outline my research methodology, research design and elaborate on used methods for primary data collection. In chapter three, I situate my research in the literature and relate photovoltaic technology to political ecology, anthropology of infrastructure, anthropology of waste and Ulrich Beck's theory of risk (1992). In chapter four, I analyze my findings from interviews with Austria's solar industry experts and link them to the toxicity of photovoltaic materials, recycling, and delegation of responsibility for PV waste risk management. Finally, I complete the chapter by linking Austria to the global photovoltaic technology's supply chains in order to highlight the uneven spatial distribution of socio-environmental risks of PV waste across geographies and argue that despite its advantageous position in terms of having an adequate local recycling and regulatory infrastructure, some of Austria's photovoltaic waste-related risks still need to be addressed.

1. Photovoltaic modules and their waste: Austrian context

To bring down its greenhouse gas emissions to zero by 2040 (iea.org), Austria has set out to decarbonize its power sector and push up current 70% renewable electricity production (bmlrt.gv.at, 2019) to a 100% already by 2030 (mission 2030). Solar power features prominently in these aspirations with energy experts projecting that it can potentially supply 15% of Austria's electricity needs by 2030 (energy-innovation-austria.at).

Currently, the share of solar is marginal in Austria's renewable electricity mix. In 2020, it covered only 3.6% of power demand (pv.magazine.com, 2021) signaling the need for at least four-fold growth, if a 15% target is to be met by 2030. The rollout of a million rooftop photovoltaic panel program, announced by Austria's new coalition government (solarpowereurope.org, 2020) is one step in this direction and a huge leap from the previously planned 100,000 rooftops solar target (pv-magazine, 2018). Simultaneously to the rooftop photovoltaic systems, utility-scale, ground-mounted solar plants are coming into the scene in the country. Made up from thousands of photovoltaic panels, these constructions often spring up on Austria's abandoned industrial sites, doing away with common solar-plant-related concerns over land use (Mulvaney, 2019) and boasting eco-conscious design to minimize the negative impact on local ecosystems (pv-magazine, 2021).

As photovoltaic technology diffuses in the country, questions over the fate of its amassing waste and proper recycling arise (Dobra & Wellacher, 2019). Researchers estimate that with the expansion of PV markets and solar power production, up to 6 million tons of waste will begin to stockpile from decommissioned photovoltaics every year from 2050 globally (IRENA, 2016 etc.) while Austria alone will generate 2000 tons of end-of-life photovoltaic waste annually already by 2031 (Dobra & Wellacher, 2019:79). The treatment of these discards, regulated by the Waste Electrical and Electronic Equipment Directive (WEEE) but only within the European Union (Mathur, et. al., 2021), will have to be managed so that depreciated photovoltaic modules don't become an additional environmental challenge. The reason for particular concern is hazardous photovoltaic content such as gallium, cadmium, indium, selenium and lead among other chemicals (Franz & Piringer, 2020, Mulvaney, 2019, Chowdhury, et. al. 2020, Kumar and Turner, 2020, Mulvaney, 2014) that can easily leach into the environment, and contaminate ecosystems if attended inappropriately. Some of these harmful materials such as lead, silver and tin are present even in crystalline silicon photovoltaics—the planet's most dominant solar power technology which represents two-thirds of all produced modules and is mainly composed of what is classified as non-hazardous materials (IRENA, 2016).

Austria, being the European Union member state, complies with the WEEE directive. Accordingly, local producers are obligated to report the quantity of produced, decommissioned, and recycled photovoltaic panels under the principle of 'extended producer responsibility' (ibid: 2). However, as researchers argue, the lack of specialized PV waste recycling facilities complicates the efficacy of PV waste treatment in Austria. Instead of such entities, PV waste is now treated by the country's waste and scrap industries that use the combination of mechanical process and manual labor (Dobra & Wellacher, 2019). While volumes of Austria's end-of-life photovoltaic panels are considered manageable at present, their inevitable increase will necessitate specialized infrastructure and possibly, a special legislation (ibid: 79).

1.1. Brief history of photovoltaics

In order to better understand the legacies that materialized in photovoltaic technology and trace forces that shaped it, this sub-section revisits the origins of photovoltaic panels. Belonging to a '…realm of three-piece suits and carefully crafted investment plans' (Flavin, 1983:11), photovoltaic technology is the joint product of scientific thought, laboratory experiments, government space programs, oil and electronics industries.

The discovery of a photoelectric effect in 1839 was followed by the production of the first solid-state photovoltaic cell in England in 1877 (Loferski, 1993). Seventy- seven years later, in 1954, while looking for a way to produce off-grid electricity for rural telephone systems (Flavin, 1982: 7), Bell Laboratory researchers improved the efficiency of solar cell technology, provoking thoughts about the possibility of their use for large-scale electricity production (Loferski, 1993). However, the availability of cheap oil and the boom of fossil fuel power plant constructions (Flavin, 1983) combined with the appearance of the first commercial nuclear reactor at that time, diverted 'massive government programs' away from photovoltaic technology (Flavin, 1982:9). Both the US and the Soviet Union space programs, on the other hand, found a practical use for solar cells by powering spacecraft satellites with them (Flavin, 1982, Flavin, 1983, Loferski, 1993, Green 2005).

In 1970ies with the onset of oil crisis, the oil industry took interest in photovoltaic technology and began to develop it for terrestrial use. The oil embargo and rising prices on fossil fuels encouraged new research programs on photovoltaic technology in Europe, Japan, the United States and the Soviet Union (Flavin, 1983: 8), expanding the technology market and dropping the costs of its production (Flavin, 1983:9). By 1980ies US and French oil companies began to pour in investments and purchase solar cell developing firms (Flavin, 1983: 39). However, as soon as oil prices started to fall, oil companies cut back on investments, giving way to manufacturers of electronics including German Siemens, and Japanese electronics giants. These new players pushed the international competition for the development of photovoltaic technology even further.

Approximately in the same period, during the transition to Reagan's administration, the United States reduced funding for all alternative energy sources, including photovoltaics. As a result, the U.S lost its leader's position in photovoltaic technology development (Loferski, 1993, Flavin, 1983) while

Japan and European countries came to the fore as they increased funding of solar cell research (Flavin, 1983).

1.2. Summarizing photovoltaic technology in Austria

In Austria, the first solar power plant appears at about the same time. The scantly available sources mention the first PV system which was erected for research purposes above 1600m sea level in the Austrian Alps in 1988. The maximum capacity of this solar power system was 30 kilowatt peak (Eder, et. al, 2020) which equals about 27,000 kilowatt hours of annual electricity production (energuide.be) or the same amount of electricity that could brew 324,000 pots of coffee (arcadia.com).

Austria's early-phase innovation period in photovoltaics was followed by the growth in the local PV market from 2003 which coincided with the passing of the green electricity bill and then by the abrupt collapse of the market in 2004 as a result of capping of feed-in tariff subsidies. After the introduction of green energy subsidy schemes and additional funding in 2013, the installment of solar systems stabilized and from 2019 started to increase, reaching 1,702 gigawatt peak (GWp) installed capacity which reportedly reduced the country's CO_2 emissions by 739,900 tons in 2019 (nachhaltigwirtschaften.at, 2019). To compare, Austria emitted 79.8 million tons of CO_2 in the same year (umweltbundesamt.at, 2021).

2. Methodology

This chapter delves into the details of the research process. Below, I outline the theoretical perspective which shaped my approach to studying the subject at hand. I elaborate on participant recruitment, data collection method, analysis, ethical considerations and limitations that I had to consider during data collection.

2.1. Theoretical approach

Political ecology

Theoretical perspectives or put differently, epistemological frames are lens that guides research questions and influence ideas about what to code in the data (Bazeley, 2013: 146). With respect to my study, such a theoretical perspective is political ecology. The approach of this perspective to environmental problems as matters of socio-political relations (Neumann, 2014: 44), its acknowledgment that socio-environmental costs of energy, in this case, of photovoltaic technology and solar power expansion, are allocated unevenly (Bridge, et. al., 2018), and the ways in which disparate places, communities, ecologies, markets and institutions are connected through the production of commodities, i.e. photovoltaics (Mulvaney, 2019), has steered my engagement with the subject of my research, the questions I probed with informants and the ways in which I interpreted the issue at hand from the obtained data.

Examination of photovoltaic waste through a political ecology lens and subsequently, problematizing it, has lead me to explore the category of risk (Beck, 1992) in relation to this technology and the distribution of its risks across time and space. Among political ecologists, the risk is defined as exposure to hazards and vulnerabilities that differ from one geographical location to another (Huber, et. al., 2017). Considering the multi-scalar aspects of my research, even though it is place-based, simultaneously it is linked to the global as well. Namely, to the market and economic relations, global commodity and supply chains, as well as global climate policy and carbon reduction imperative which is the impetus for the introduction of new, regional level European Green Deal policy on the authority of which Austria's current national carbon reduction targets are set and photovoltaic upscaling is taking place. Hence, due to the interconnectedness of local and global in my research, I analyze global forces (Gille & Riain, 2002) by anchoring myself in the concrete place, specifically, Austria which I see as a point of intersection of global, regional and local forces, policies, regulations, techno-scientific knowledge on photovoltaic technology and its waste management. Thus, methodologically my research is a case study (Bazeley, 2013) but its subject of interest does not exist in isolation, disconnected from the rest of the world or the ongoing socio-technical and economic developments. Rather it is bound to multiple geographical localities as well as global climate policy, economy and regional regulation on electronic waste management.

2.2. Recruiting participants

The core criteria based on which I defined the sample group for my study was that it had to represent key players of Austria's contemporary photovoltaic sector. This is because, I wanted to study the 'risk consciousness' (Beck, 1992) of those who shape the solar power technology, thus its impact on the environment and society. As a result, I targeted experts from across the Austrian photovoltaic sector, ranging from photovoltaic manufacturers to the knowledge- producing, solar technology research center engineers and scientists, installers, lobbyists, recycling experts and other key stakeholders.

The recruitment process was entirely online-based. After conducting online research for identification of those stakeholders who specialize the expansion of solar technology in the country, I compiled the contact list and reached out to them with a brief introduction of my research and myself which was followed by the request of an interview and a consent form containing a detailed explanation of participation terms. In the end, I obtained consent on participation from ten informants. Snowball method (Seale in Phellas, et. al., 2011) became an important sampling strategy in the recruitment process as some of my informants put me in touch with otherwise hard-to-reach interviewees. Snowball sampling, a suitable method for studying social networks (Heckathorn 2011) and hidden population (Seale in Phellas, et. al., 2011), tends to limit the diversity of demographic groups and ties researchers to participants with similar characteristics or experiences who are also part of the same network (Seale in Phellas, et. al., 2011). On the other hand, snowball sampling is useful when the goal of the researcher is to study elite groups which is why it helped me to discover important actors in Austria's photovoltaic sector.

Overall, the recruitment and interviewing process continued over the span of eight months, from October 2020 to May 2021. In the end, I conduct interviews with 10 experts from Austria's solar sector. The list of stakeholders that these experts represent is included in appendix (1).

2. 3. Collecting data

To collect primary data, I used the interview method. Seven out of ten were semi-structured interviews. Because of coinciding lockdown periods of COVID-19 pandemics, these interviews were held through video calls, in English with a duration of a minimum 45 to maximum of 75 minutes and recorded as video files for further transcription. Three informants who agreed to the e-mail interviewing format only, were provided with a list of open-ended questions. Two of the interviewees received a list of nine questions and one of them, a list of five questions. This variation was necessitated by differences in informants' roles in the Austrian photovoltaic sector which required adjusting questions to their expertise. The general interview guide which was used with the research informants is available in appendix (2).

As expected, the written e-mail interview format was characterized by inflexibility and asynchronicity due to the displacement of time and space (Bampton & Cowton, 2002) between the subject and the researcher. Importantly, the impossibility of gleaning non-verbally communicated information and witnessing the articulation of spontaneously formed thoughts that face-to-face or even live video-interviewing allows, made e-mail interviewing a less expressive method of data collection. However, this has not diminished the validity of acquired data and in certain sense, e-mail interviewing has provided some advantages such as the opportunity for reflection at the respondent's own pace, and removing the need for transcription by affording written down data for the researcher (ibid).

Video interviewing on the other hand was conducted in real-time. This format provided excellent conditions for conducting semi-structured interviews. Aside from the fact that none of the respondents had any problem with technology access, the additional advantage of the medium was that informants engaged from places that they picked and felt convenient in.

The secondary data which is also present in my research and provides the background information was obtained from various governmental and organizational reports on renewable energy and technology innovation in Austria, as well as scientific articles and media materials from both English and German language sources.

Given the research question of this study, I considered semi-structured interviewing to be the best method for probing open-ended questions with top experts around puzzling aspects (Adams in Newcomer, et. al., 2015) of photovoltaic technology. By allowing off-the-script conversations with the interlocutors (Bryman, 2012), semi-structured interviewing helped me to keep an open mind about new concepts and hypotheses that the conversation data pointed towards (ibid:12). Furthermore, this particular type of interviewing enabled me to get access to the insider's view (Bazeley, 2013) in the photovoltaic sector, and my interlocutors' way of thinking in relation to photovoltaic waste, her/his risk judgements and visions about potential solutions.

Before developing the final version, the interview guide was redrafted several times. The initial number of questions was reduced and remaining ones redefined according to the research question as well as the core themes that were identified in parallel to the process of interview question revision, reading of photovoltaic technology research materials and pilot interviewing. The initial draft of the guide was used in a pilot test interview (Newcomer, et. al., 2015). However, the obtained material was not included with the collected primary data since the goal was to test questions and modify them together with preliminary themes according to the results of the pilot interview.

Overall, the interview process was characterized by flexibility of structure which encouraged extensive responses from informants and their reflexive engagement in conversations.

2.4. Enter data analysis

The foundation for primary data analysis was laid with transcription of recorded video-interviews. Listening to informants retrospectively, and seeing textual versions of conversations became initial stages of my immersion in the data. Repeated reading of transcripts and occasional returns to video files enabled me to make new findings that did not catch my attention during interviewing but when approached retroactively, were easier to identify.

After building the sense of the whole data which was accompanied by keeping reflections in the form of notes, the following step in the analytic process demanded a more systematic and methodical approach, so I switched to open coding. I coded each paragraph in a descriptive manner which helped me to name and pin down topics that could later evolve into concepts or analytical categories (Bazeley, 2013: 126). Once open coding was completed, I reviewed the material to see how codes could be categorized and what concepts could be generated from them. In the process, it became apparent that rather than focusing only on the fragments of the data, it was necessary to take a step back and revisit the surrounding texts to reconnect with the larger context. In other words, I needed to move from details to breadth again (ibid: 143). Alternating between fragments that were codes, and the whole that were meaning units (ibid: 144)—namely, several paragraphs—with the intent to understand the speaker's interpretations, eased the process of moving from the stage of description to the stage of interpretation and theme generation. Once I had my themes, the writing process began.

2.5. About ethics

Before I move to reflections on the practical limitations of this research, ethical aspects need to be outlined. In this regard, the foremost principle that I needed to adhere to over the course of the primary data collection was obtaining informed consent (Neuman & Robson, 2014).

I introduced my research and myself to potential informants via e-mail. Once they confirmed that they would participate, I provided a consent form which contained details about the purpose of the research, the subject of interest, the scope, the sample group, the format, terms of data storing, confidentiality, and the graduate program for which I was conducting the study. As a result, I ensured that all informants had a clear idea about what they were giving voluntary consent to. I should note that the angle of research was modified in the section of research description as I continued to refine my focus during data collection process. In the beginning of every interview, participants were informed that some modifications were likely to be made to the research but without changing its core subject of interest.

Anonymity and confidentiality (ibid: 2014) were the principles that I chose to abide by and include in the consent form as a default at the very outset of the data collection. I made this decision when I was negotiating to recruit some of my informants who asked to keep their identity confidential as a non-negotiable condition of participation in the study. I extended this term to every informant which is why only the specialization areas are provided in the list of study participants and the interviewee's names are replaced by numbers.

2.6. About limitations

Practical limitations impact research (Neuman & Robson, 2014: 109). In this respect, access and time were main issues that shaped both my approach to how I designed the study, and to certain extent, its outcome. Language and pandemics-related restrictions were those access-related factors that kept me cognizant of limitations and subsequent need of flexibility from the very beginning. It was clear that COVID-19 lockdowns would be inevitable so, I had to keep in mind that the ethnographic method which requires on-site presence and observation would be an unfeasible undertaking. In contrast, interviewing could be relied upon as the primary data collection tool in given circumstances. This method would be especially practicable during lock-down periods because video-conferencing software had already become a standard medium for in-person, and professional communication. Given that my sample group was going to be what in social research is sometimes referred to as the elite group (Bryman, 2012), namely, experts who specialize in photovoltaic technology, I expected that they would have access to such software for their daily professional activities. Luckily, I was right to assume so.

Another access-related limitation was the language of communication. With my basic proficiency in German, I focused on English speaking informants. Although the likelihood that my target group would be speaking English was high, the language still became an additional barrier which obstructed my access to those stakeholders who only speak German.

Restraint in time which meant having only a few months to conduct and write up my research in the conditions of pandemics, had determining effect on its content and form as well. Limitations in time but also restrictions in mobility and accessibility, affected how I formulated my research question, the research technique I chose and the type of data that I collected.

3. Literature Review

Photovoltaic waste is under-researched in anthropology. Scant studies that have emerged on the topic only recently, focus on informal repair cultures of broken-down solar modules as alternatives to dominant narratives of waste management (Cross & Murray, 2018) or explore social ruins after the break-down of photovoltaic technology (Kumar & Turner, 2020). In line with anthropological tradition, these studies take interest in the experiences of those who live on the socio-economic margins, typically in the Global South (Alexander & Reno, 2020) while accounts from Global North are barely present on the subject. Given this gap, I explore the matter in a highly industrialized locality of Global North and research the community of photovoltaic technology experts who produce or help the expansion of these carbon-free electricity-producing devices in Austria. To develop my argument, I draw from the theoretical approach of political ecology which is useful in tracing hidden costs of photovoltaic waste and the distribution of its risks. In addition, I adopt the concept of risk as theorized by sociologist Ulrich Beck (1992) and bridge these theories with the anthropology of infrastructure and waste.

3.1. On political ecology and my research

With its roots in critical social theory, historical materialism and interest in socio-environmental justice, political ecology teaches that socio-political context affects not only how environmental problems are seen but the choices that become available for addressing the same issues. This theoretical approach questions 'conventional scientific and management approaches…' (Bridge, et. al., 2018: 165-166) that are employed for tackling socioecological matters. Broadly speaking, political ecology raises concerns about the role of power in shaping human-nature relations (Biersack & Greenberg, 2006) and acknowledges the unequal distribution of costs and benefits of environmental change (Bryant & Bailey, 1997). In my research, I contribute to the following discussions from political ecology: Changes in environmental and ecological conditions result from political and economic processes (Robbins, 2011: 19-20), paying attention to scales, namely, connecting local with the global is crucial (Biersack & Greenberg, 2006) in thinking about how environmental problems affect different places since scales are '…nested within another, with local decisions influenced by regional policies, which are in turn directed by global politics and economics' (Robbins, 2011: 20). I also follow the connections between supply chains, manufacturing and disposal of photovoltaic technology from a political ecology perspective to uncover the environmental and social costs of solar waste.

Even though political ecology is criticized for its relative weakness of theoretical coherence (Biersack & Greenberg, 2006), its strength lies in interdisciplinary character (Biersack & Greenberg, 2006, Robbins, 2011, Bassett & Peimer, 2015). I take advantage of such theoretical flexibility of political ecology to develop my argument on socio-environmental risks of photovoltaic waste.

3.2. On photovoltaics from political ecology lens

To consider the broader field of energy from a political ecology perspective in the European context, since the industrial revolution energy transitions '…have been achieved through a global processes of unequal exchange' (Bridge, et. al., 2018: 167). Even today, this tendency is unfolding in the form of moving '...carbon-intensive production elsewhere' (ibid: 168). However, as some studies demonstrate, the transfer of industrial production from Europe to foreign lands and the relocation of negative effects to remote areas has been mutually damaging for some communities in leading European economies too, resulting in their economic, political and social devastation. One example is the marginalization of the German Bitterfeld region as a consequence of the local photovoltaic manufacturing industry's collapse (Brock, et. al., 2020) which turned the region into a 'sacrifice zone' of once promising green industrial development (ibid). The case of Bitterfeld shows the photovoltaic industry's precarious side, its commitment to economies of scale, its dependence on global market rules and mobility of capital (ibid:18) that in turn make this technology yet another global commodity, susceptible to unsustainable industrial processes, source of externalized waste, pollution and socio-economic inequalities (ibid: 1)

In a somewhat similar fashion to Brock and his colleagues, Hornborg (2016) considers solar energy '…an expression of global processes of capital accumulation which fossil fuels have made possible' (ibid: 119). Examining solar energy from the political ecology perspective, he points to environmentally harmful effects of photovoltaic technology manufacturing, including pollution, greenhouse gas emission, resource-extraction and resource intensity (ibid: 119). He poses questions about the inequality of access to solar energy and takes interest in who pays the price for its availability with their resources and labor (ibid: 125). Thus, he argues that solar technology not only fails to solve the problems of clean energy accessibility globally but its green promise becomes questionable as well. He suggests that technologies, including photovoltaics, are not autonomous from 'societal power structures, symbolic systems and global resource flows' (ibid: 119). Readers will see that some evidence to these arguments will arise in my research from conversations with Austrian experts and stakeholders of photovoltaic industry.

3.3. On science, experts, and technology from critical standpoint

Photovoltaic technology emerged from the same realm of laboratories, engineering and science as electricity, 'the foundational apparatus of modernity' (Boyer, 2015: 532). In critical theories about technology and science (Feenberg, 2010) the techno-scientific rationality which produced them, rather than being an apolitical, value-neutral form of knowledge, is receptive to social influences (ibid: 158). It is this critical approach to scientific and technical knowledge that I engage with in my research and accept that scientists, technical experts and engineers are influenced by their own 'professional cultures and interplays of interests' (Sismondo, 2010: 168) as well as broader political, cultural and policy processes. That science and technology is interconnected with '…the circumstances of their production' (ibid:11) has been recorded by anthropological studies of experts who, as it turns out, are firmly rooted in '…very particular conditions of knowledge production and circulation' (Harvey & Knox, 2015: 9). At the same time, as much as knowledge of technical experts are interlinked with social, cultural and political realms, their practices are '…reality changing interventions into the lifeworld' (Feenberg, 2010: 178) with very concrete effects on social, and natural ecosystems. However, this mutual construction (Shackley & Wynne, 1995) of the social and techno-scientific domains does not take place outside of nature. In these relations, science even 'determine[s] what nature is' (Sismondo, 2010: 32) but occupies such a separate position from it that once transposed from the artificial environments of laboratories into the messy world (ibid: 167), the ideal models of science generate risks and unintended consequences.

3.4. On photovoltaics as infrastructure

Electricity is unable to fuel everyday activities and entire economies without machines, wires and generally speaking, special infrastructure (Bakke, 2016: 11) to which photovoltaic technology belongs as well. Anthropologist Brian Larkin defines infrastructure as built networks through which goods, ideas, people, power and finances flow. It is not only a thing but '…also the relation between things' (Larkin, 2013: 329) which reveals 'political rationality' (ibid: 328) and the idea of progress. Thus infrastructures are fundamental to modern society and its aspirations towards 'realizing future' (ibid:332). Even though infrastructures are material entities in the first place, materiality is not their only dimension. They operate on the affective level too and accommodate fantasy, desire (ibid: 333), imagination, and ideology (Anand, 2011). Because of such complexity, infrastructures are increasingly recognized by social scientists '…as sociotechnical assemblages…' (Harvey & Knox, 2015: 5) that bring together a particular arrangements of ideas, materials, and people. In other words, they are relational entities (Bowker, 2018, Star,1999) through which politics are enacted (ibid: 5).

Yet, as infrastructures shape everyday life with the promise of modernity, safety, freedom, economic growth and progress, the same narratives are challenged by the fragility of infrastructures, their occasional failure, and even abandonment (Anand, et. al, 2018: 3). Due to their materiality, infrastructures, including photovoltaic modules, break down and eventually become obsolete. Simultaneously to progress, modernity, and growth they can engender degeneration, ruination and risk too (Howe, et. al., 2016). While made to mitigate risk, infrastructures can paradoxically produce new risks (ibid: 556) which is why some scholars encourage us to reflect on ruins and the capability of infrastructures of adapting to '…unknown nexts…' (ibid: 558). Keeping in mind such multifarious nature of infrastructures, and especially their fragile, risk-producing qualities is useful for examination of the precarious side of what is known as clean electricity-generating photovoltaic technology. To accomplish the task, first, I will define the concept of risk as understood in sociological thought.

3.5. On risk

In everyday language, the meaning of risk is 'the possibility of harm' (Van de Poel & Fahlquist, 2013: 107) whereas in a techno-scientific context, this concept is defined as 'the product of the consequences of an unwanted event' (ibid: 110). The sociological conceptualization of risk is contextual. In this school of thought risk can neither be reified nor naturalized which means that risks are always deeply rooted in socio-cultural and historical context, influenced by '…the activities, technologies and instruments that serve to map them' (Lindskog & Sundqvist, 2013: 77).

While there are several major theories and perspectives on risk in social theory (Douglas, 1992, Luhmann, 1993, Beck, 1992), I draw from the social construction approach where risk is 'a product of social processes' (Lindskog & Sundqvist, 2013: 84) which is '…irreducible to technical measures' (ibid: 84) alone but how different actors 'frame, define, understand and manage risks' (ibid: 84) is at the center of analysis. Ulrich Beck's risk society (1992) which is focused on the environmental question and the distribution of risks, is the guiding theoretical framework of risk in my research. With Beck, the risk is 'a systematic way of dealing with hazards and insecurities induced and introduced by modernization itself' (Beck, 1992: 21). It results from 'political decisions and human action' (Lindskog & Sundqvist, 2013: 88). Modern societies are shaped by risk-producing techno-scientific progress (Beck 1992: 45) where risks inflict harm on a global scale because they are no longer delimited in time and space (Beck, 1992: 22). Furthermore, the knowledge about risks of pollutants is susceptible to interpretation, minimization, or dramatization before they reach the public because these risks only exist as scientific knowledge at the beginning (ibid: 23).

Overspecialization or an 'isolated analytical approach' (ibid: 179) is another important theme that I apply in the analysis of my research. According to Beck, overspecialization generates new risks as it encourages the design and implementation of selective solutions and 'patchwork' (ibid: 179) measures to problems that require systemic and political approaches. In the analysis chapter, it becomes clearer why overspecialization deserves critical scrutiny in the context of photovoltaic waste management.

3.6. On photovoltaics and waste

That clean technologies are not inherently clean becomes evident when their materiality and energy input is considered. Examined beyond carbon-free electricity production, photovoltaic modules too can be hazardous for the environment not only because they become waste at the end of their life-cycle but because their manufacturing produces toxic waste too (Mulvaney, 2019). Categorized as electronic waste, treatment of photovoltaic discards, similar to other inorganic waste requires 'scientific expertise' coupled with 'complex chemical and mechanical technologies' (Beck 1992 in Gille, 2007: 26). Because it can cross '…natural and manmade boundaries' (Gille, 2007: 26-27) easily, inorganic waste also requires global cooperation (ibid: 27).

Anthropologists who mainly focus on immaterial aspects of waste such as 'social habits, cultural representations and political hegemony' (Martinez, 2017:348), otherwise put, approach it as 'a symptom of culture and social relations' (ibid: 347), have yet to engage with photovoltaic waste extensively. Even though there are scholars who turn to the subject by emphasizing uneven distribution of harms of solar waste which in underserved areas begets social ruins but also sparks informal economies of repair and care (Cross & Murray, 2018, Kumar & Turner, 2020), their studies concentrate on micro and informal practices. At the same time, industrial practices of waste production, including that of the electronics industry (Lepawsky, 2020), agriculture, retail, or biomedicine feature less in anthropological accounts (Alexander and Reno, 2020: 7). With regard to photovoltaic industry waste, its recycling and chemical stewardship, social scientists from other fields touch upon the issue and explore its management in the context of environmental policy, commodity chains and energy justice frames (Mulvaney, 2019). Unlike ethnographic studies of solar waste in the Global South, the focus here is placed mainly on formal institutions, advanced technologies, regulations and policy improvement in highly industrialized countries. Where sophisticated technologies and regulations support end-of-life photovoltaic treatment and recycling, one may assume that there is little to no reason for concerns over environmental risks, or blind spots in photovoltaic waste management but existing research suggests that these risks persist in such environments too (Mulvaney, 2019). My thesis contributes to this line of thought and examines photovoltaic waste from the perspective of photovoltaic producers, recycling experts and photovoltaic technology developers. The rationale behind this approach is that most of the pollution and waste come from industries (Lepawsky, 2020, MacBride, 2013, Alexander and Reno, 2020), meaning that the reduction of existing PV waste risks hinges largely on the makers of the technology.

4. Analysis

In this section, I examine how scientists of Austrian photovoltaic research institutes, and other key stakeholders from the photovoltaic industry, reconcile socio-environmental risks of photovoltaic waste. As it was previously established, solar panels, including crystalline silicon modules—the most common and least hazardous types of photovoltaics in terms of material composition—contain toxic substances (Weckend et. al, 2016, Mulvaney, 2019), raising questions about the environmental justice of solar power transitions and risks that improper treatment of their waste poses to the ecosystems and human health (Mulvaney, 2019).

In sociological thought, the risk is '…connected to actors' activities' (Lindskog & Sundqvist, 2013: 75). It is never decontextualized, existing on its own. Rather it is the outcome of how actors 'understand and manage certain phenomena' (ibid: 77). When applied to this research, the sociological definition of risk suggests that the industry stakeholders are shaping socio-environmental consequences of photovoltaic technologies but they also act and produce knowledge within the constraints of a complex ecosystem which represents the intermingled web of law, bureaucracy, infrastructure, policies, politics, and market relations that often operate not only dialectically, but at different scales too. Besides the role of stakeholders, there is the additional dimension of materiality and the limits that it sets when risk elimination is considered through photovoltaic waste treatment technologies. As it will become clearer in the chapter, some solar module materials reveal themselves as unstable, unruly entities (Benett, 2010) that affect the organizational and technological setup of Austrian photovoltaic industry stakeholders, thus disclosing new aspects in the management of photovoltaic waste risks.

4. 1. End-of-life PV waste recycling: 'a subordinate' issue

To summarize the interview data, the informants of this study forecast that potential negative environmental consequences of photovoltaics can and will be curbed through right technologies. The unresolved questions that surround supply chains of photovoltaics, production waste (Mulvaney, 2019), recycling of decommissioned solar modules (Mulvaney, 2019, Hoppmann, et. al., 2013, Franz and Piringer, 2020) and other issues the research literature is increasingly paying attention to, do not outweigh the general sense among research informants that solar panels are not only clean and timely energy-producing technologies but '*competitive*' and '*cheapest form of energy*' which is also '*more or less maintenance free*', '*well accepted by society'* and easy to implement '*compared to other renewable power plants such as wind or hydropower…'*.

A thin-film photovoltaic panel producer whose company makes technology for various surface application that can generate energy from '*a lot of existing surfaces*' reconciles contradictions of photovoltaic technology in the following words:

> *It always depends on what you compare [PV technology] to…of course there are disadvantages in some perspective...of course [there are] materials…which are toxic which are maybe problematic to produce or problematic to recycle but then it's always the question of what are the other alternatives and from this perspective, I think most of the time PV has the winning argument. For me at least…disadvantages always depend on the comparison…'* (Informant 4, Jan. 19, 2021)

A more variegated picture emerges when photovoltaic waste comes into focus and the question of environmental risks becomes more explicit. As mentioned, concerns on waste follow photovoltaic modules throughout their life cycle (Mulvaney, 2019) similar to other electronic commodities (Lepawsky, 2020), even though in photovoltaic manufacturing less hazardous materials are used than in the manufacturing of electronics (Mulvaney, 2019: 25). Concerning this issue, some informants believe that in Austrian public discourse photovoltaic waste is a *'prominent'* topic. As one of Austria's top photovoltaic technology expert puts it:

> *'…people ask…if [PV]is installed can it be recycled? What is with all the water used for producing the stuff? These are the questions that are in the center of the public mind together with questions like, will it ever bring back its energy which was used to produce it?'* (Informant 1, Nov. 16, 2020)

Another interviewee underlines that public discussions on photovoltaic waste from its production process, is not a novel theme in Austria but the end-of life PV waste, is. For emphasis, he adds that together with his team, he '*…started the public discourse',* on the topic and still keeps promoting it through photovoltaic technology-dedicated conferences. As his statement indicates, the end-of-life photovoltaic waste is just beginning to take hold in the expert community but remains outside of general public's attention. What's more, other informants comment that the end-of-life solar waste is not a trending topic even among key stakeholders. This is what a photovoltaic recycling expert points out:

> '*From waste management perspective, I think it is still not a really big topic when I talk to the companies*' (Informant 2, Dec. 1, 2020).

In a similar vein, a prominent Austrian PV waste collection company representative emphasizes that in public discourse the end-of-life recycling of solar modules '*unfortunately plays a subordinate role…this also applies to the manufacturers*' (Informant, 7, Jan. 15, 2021).

4. 2. Coping well with end-of-life PV waste

Despite the unfamiliarity of the general public with implications of end-of-life PV waste fallout and the unpreparedness of key photovoltaic sector players for the looming problem, the recycling of the decommissioned modules, similar to other electronic waste is common practice in Austria (Dobra and Wellacher, 2019). However, the rates are '*really low*' as the representative of a collection company discloses. The table below clarifies the informant's assessment in figures but also reveals a significant difference between the collected and treated photovoltaic modules. The reason for this discrepancy as the interviewee admits, remains unknown.

	2017	2018	2019
PV collected	22,2 t	7,8 t	2,5 t
PV treated	13,8 t	7,5 t	2,3 t

Source: *Tätigkeitsbericht Elektroaltgeräte Koordinierungsstelle GmbH* [1]

Austrian photovoltaic waste researchers have already noted that the actual number of end-of-life PV waste in Austria is higher than reported (Dobra and Wellacher, 2019: 78) but the question about the possible fate of the unrecorded devices after they become invisible to the system, is not probed.

On another note, legislative mechanisms that prohibit the disposal of untreated photovoltaic modules into the environment and make their collection, registration, treatment, and proper disposal mandatory, do operate in Austria. These mechanisms include the national—Austrian Waste Treatment Obligations (ris.bka.gv.at, 2017)—and the regional level Waste Electrical and Electronic Equipment (WEEE) directive (Dobra and Wellacher, 2019) which obligates all members of the European Union to comply with photovoltaic waste treatment standards.

1. *Tätigkeitsbericht Elektroaltgeräte Koordinierungsstelle GmbH*, (2019) [online] Available at: https://www.eak-austria.at/presse/TB/Taetigkeitsbericht_2019.pdf
Tätigkeitsbericht Elektroaltgeräte Koordinierungsstelle GmbH, (2018) [online] Available at: https://www.eak-austria.at/presse/TB/Taetigkeitsbericht_2018.pdf
Tätigkeitsbericht Elektroaltgeräte Koordinierungsstelle GmbH, (2017) [online] Available at: https://www.eak-austria.at/presse/TB/Taetigkeitsbericht_2017.pdf

Concerning photovoltaic module recycling, informants of this research refer to these regulatory frameworks and express confidence in the Austrian waste management system too. *'We have a lot of good recycling companies in Austria'* comments an interviewee whose sentiment is shared by other informants as well. According to them, in combination, these regulations and recycling practices, render toxic or difficult to recycle parts of PV modules manageable, containable and therefore, unproblematic for environmental or human health concerns. As one key interviewee put it:

> '…*there is not a lot of materials* [from photovoltaics] *that are directly landfilled, mostly because that's just not allowed… it's not like in Europe these panels are thrown into the woods or buried'.* (informant 2, Dec. 1, 2020)

Besides the fact that the waste management legislation is seen as an organizing mechanism and a dividing line between an efficient system to which Austria is part of and an underdeveloped one elsewhere, the same informant emphasizes that the existing waste recycling plants, even though none of them are specialized in solar module treatment exclusively, still manage to cope well with current PV waste stream. The reason is that '…*the volumes [of PV waste] are just small'*. For accuracy purposes, end-of-life solar modules comprise only 0.02% w. of Austria's all collected electronic waste (Dobra and Wellacher, 2019: 78).

In a similar manner, an interlocutor from a leading Austrian photovoltaic production company underscores that the amount of PV waste which is returned to them for forwarding to the recycling partner for treatment, is minor:

> *'For the moment, we don't have a lot of modules coming back to us…you have maybe one or two pellets* [one pellet consists of twenty-four modules] *per month which are damaged during mounting or by hailstorm, etc. …and we have a local recycler who is picking up modules from us doing the recycling work'* (informant, 6, May 4, 2021)

In contrast to the present situation, however, the producer notes that from 2029, when the company will see an increase in returned end-of-life photovoltaic modules, their management will become far more complicated. The rise in quantities will require the adaptation of the producer's current PV waste management setup and expectedly, the country's electronic waste recycling system too:

> *'We know that in the future when the amount of end-of-life modules will rise up, then it will be hard to do it in the same way, like we do it now because when it is not one but thirty pellets, then you cannot handle everything at the headquarter…and also from the logistical point of view, we will need a system which also can provide us collecting points where customers can bring the modules to and then these modules can directly go to the recycler…'* (Informant 6, May 4, 2021).

The producer's account echoes the existing research which projects that the increase in PV waste volumes will drive the development of end-of-life PV recycling system in Austria (Dobra and Wellacher, 2019, 78) but the arrival of more waste also makes a broader-scale, thorough transformation inevitable, requiring PV manufacturers' altered capacities in managing end-of-life PV discards.

4. 3. Toxicity of PV materials

Liboiron and their colleagues socialize toxicity (Liboiron, et. al., 2018), and define it as '…a disruption of particular existing orders, collectives, materials and relations' (ibid: 334). Toxicity in this line of thinking goes beyond 'harm at the cellular level' and represents not something which is '…given in advance by nature but is stimulated, constructed, rehearsed and contested through a myriad set of social, epistemological, historical, economic, material, biological and governance systems and structures' (ibid:334). Considering how toxic photovoltaic materials have been brought into existence through industrial and political processes that have exposed some social groups to pollution and some ecologies to degradation (Mulvaney, 2019), the photovoltaic module toxicity has become the agent capable of disrupting pre-existing natural, technological and social order at one scale but producing a different, carbon-free energy order at another (Liboiron, et. al., 2018: 335).

As noted previously, some toxicants or materials with the ability to harm (ibid: 2018), are present even in crystalline silicon modules that contain the least amount of problematic substances compared to other, more innovative solar technologies. These modules make up 95% of the global market share (Mulvaney, 2019:15) and 96% of all installed solar systems in Austria (informant 3, Dec. 1, 2020).

To make a point about the acceptable levels of toxicity of his company-produced modules, the solar panel manufacturer emphasizes during the interview:

> *'…a very important point is that we talk about crystalline modules, [and] no thin layer panels where you have highly toxic materials inside. The crystalline technology is the oldest technology in all renewable market and the only thing you have inside this package…is lead. We need lead for the covering of the ribbons but the rest of the materials are clear'* (Informant 6, May 4, 2021).

Along the same lines, a thin layer panel producer relativizes his company's modules and argues about their material and resource-efficiency:

> *'…the basic materials [we use] are copper, Zinc, tin and Sulphur. These are materials that are abundant on earth. That's also a very important feature of our technology that we rely on materials which are abundant and non-toxic. In contrast, there are other flexible technologies that have arsenic which is toxic…and there are technologies that have indium and various scarce materials…'* (Informant 4, Jan. 19, 2021)

As readers may notice, not only does the presence of toxicant defy the logic of material purity of crystalline silicon modules but more toxic types of thin layer panels are brought to the attention as well. Ulrich Beck (1992) coins this type of comparison as relativizing, a tactic which allows producers in the techno-scientific fields to minimize risks of one product by underlining the risks of other, usually more hazardous ones (Beck, 1992: 31). The goal is the legitimization of one's own product, thus securing profits (ibid) but the argument of economic gain alone seems reductionist when applied to this case. Especially, when the broader context is considered where the Austrian solar industry is beginning to operate within a climate-conscious political and economic order and the producers dedicate themselves to the mission of carbon-free power technology provision.

4. 4. Toxicants in PV recycling and unruly materials

What makes the matter even more complex is that the constituting components of solar panels are not the only source of toxicity when the eventual environmental implications are considered. When it comes to solar waste treatment, the recycling and the recovery of materials too require the addition of toxicants.

Recycling is the process of the separation of materials that get rerouted into manufacturing (MacBride, 2013). As a concept and a practice, it enjoys strong moral and political salience which is owing to its intent of saving natural resources (Alexander and Reno, 2012). As an industry, recycling is a great economic success (MacBride, 2013) but also the crucial component of environmental reform (Alexander and Reno, 2012) and green growth discourse which promotes the idea that industrial production and economic growth can exist in harmony with the environment (Dale, et. al., 2017). But a more critical look at recycling suggests that as a practice and movement, it has targeted individual consumers more than industries that produce most of the solid waste and resort to burning or burying it rather than recycling. Besides, recycling has not been effective in addressing 'the increasing rates of global material extraction' (MacBride, 2013: 4), meaning that it has failed to deliver one of its biggest promises—conservation of resources. Finally, recycling of certain materials, including glass, as it turns out, takes more energy than the use of virgin materials (Gille, 2007), thus the energy intensity of some material recovery has the negative impact on the environment in the form of emissions (Cooper, 2016). Notably, 90% of a silicon crystalline solar panel is composed of glass (Weckend, et. al., 2016).

Going back to the subject of the discussion, it is evident that recovery of solar module materials in full compliance with green principles can be challenging due to the necessity of chemical use in the process. In this regard, solar waste is similar to other electronic waste that involves contaminants for the conversion of discards into reusable material (Alexander and Reno, 2012). A crystalline silicon module manufacturer's quote reveals precisely this as he highlights the difficulties that the recovery of some PV components create and the choices that they have to make between following the company's green ethics and using toxicants for PV component in recycling:

> '*The main problem…for the moment is the encapsulant, the EVA foil...[which] is really a recycling challenge because the material itself dissolves when you are really taking out hard chemicals which we don't want to use because we are renewable and in the recycling there should be the same thinking that we are bringing in the daily business*' (Informant, 6, May 4, 2021)

On the same wavelength, another interviewee points out that to improve the photovoltaic technology, and ultimately, reduce its negative impact on the environment, it is crucial '*to get the recycling rates up*'. This, however, means solving a two-fold problem: finding ways to '…*bring down the energy it takes to recycle*' and decreasing toxic agent use because:

> *'in the recycling process, you also use toxic materials like acids and so on, and part of this is also the waste'* (Informant 1, Nov. 16, 2020)

As one can see, despite its green credentials and resource-conservation goals, the recycling of solar modules in fact, potentially increases environmental risks which is why those who work on the photovoltaic technology in Austria, stress that the efforts to overcome these limitations are constantly being made in specialized research.

In addition to energy intensity, the toxicity of some PV materials, and the use of chemicals in recycling, the material agency features in conversations with research informants together with shortcomings of PV recycling infrastructure. Most of these issues come together when a scientist who specializes in PV recycling describes details of the photovoltaic waste treatment:

> *…the thing that does not get any attention nowadays in [PV] recycling are the polymers because usually you have those fluorine polymers and fluorine is hazardous… therefore you don't really want to even get it back. And the EVA, the encapsulant you have to destroy it to be able to recover other materials from it… It's not always happening. Usually the fractions that you don't get back for recycling end up in a thermal process… Of course, if you treat something thermally, you have some residues, ashes, stuff like that. But you don't have specific plant where it's just PV residues being treated thermally so it ends up in mixed ash or bottom slag from different materials where you can't say that this is specifically PV residue* (Informant 2, Dec. 1, 2020)

It is true that thermal treatment or the incineration of solar panel components generates energy from otherwise hard-to-recycle parts but the problem is that incineration produces its own waste, both in the form of hazardous residues and emissions that ideally require further, complex technologies of processing (Gille, 2007). Thus the agency of materials which often determines how recycling technology can or cannot change and develop (Gille, 2007: 214), becomes an obstacle, especially when synthetic and inorganic matters are involved (ibid: 25-26). On the other hand, when speaking about materiality and its tendency to 'de-centre human agency' (Knox, 2015: 105) which can easily create the illusion that materials are autonomous from social relations, it should be recognized that solar power technology, like other electric power systems, is the cultural artifact (Hughes, 1993: 2), meaning that it is also situated in the political domain, and represents the assemblage of particular ideologies and materials that can change with decisions.

4. 5. Passing the hot potato

Shifting of responsibility to recyclers and other stakeholders when questions concern the end-of-life photovoltaic waste management, thus handling of environmental risks linked to them, is another recurring theme in interviews with the informants. For example, a major Austrian energy provider which constructs photovoltaic systems and is engaged in the upscaling of solar power points to the photovoltaic research centers and recyclers when inquired about its own role in handling discards of end-of-life photovoltaic modules. This provider who among other things, invests in solar systems, discloses that it is '*constantly collecting knowledge…and following the latest disposal technologies developed by research centers*'. After their solar systems get decommissioned, this provider '*orders specialized companies to care about the proper disposal of PV waste*'.

Similarly, a photovoltaic manufacturer who is legally bound to take-back decommissioned or defective solar modules and ensure that they are treated under extended producer responsibility (Dobra and Wellacher,2019, Mulvaney, 2019, Chowdhury, et. al. 2020), when asked about the details of toxic component processing in the end-of-life modules, responds the question in the following manner:

> '*The detailed process of the decommissioning is not our main expertise. This is the topic for the recycler…*' (Informant 6, May 4, 2021)

On the one hand, the delegation of responsibility to specialized stakeholders, and even knowledge-producing research centers, is a legitimate response considered that the system which underpins solar power is technologically complex where tasks are divided among different agents who operate within strict limits of expertise. This type of sharp division in expertise or as Beck terms it 'overspecialization' (1992) carries a great value in the techno-scientific field. Namely, it allows effective problem-solving and productivity within a bounded sphere of concern but it comes with downsides too. Overspecialization generates new risks by obscuring the bigger picture through isolated knowledge generation, meaning that engineers and producers sometimes remain unaware of what happens to the technology of their own making at the other end of the pipe or what its broader implications are. This phenomenon is crystallized in a solar cell engineer's response which he provided to the question about his knowledge on how hard-to-recycle components of photovoltaic modules are treated in Austria:

> *'I don't know. I think they are lost and deposited…or they are stored in salt mountains. This is the wrong way to do it because then it's wasted, and I have heard that it is not lucrative to collect small amounts of silver or copper in PV modules but I hope that they find solution or that prices of these components rise so that the complete recycling process is lucrative'…* (Informant 5, Apr. 16, 2021)

All of these quotes have one thing in common—gaps in knowledge about the afterlives of the most problematic materials of photovoltaic technology because the issue at hand lies beyond the sphere of concern and specialization of these stakeholders, even if the goal for all of them is the same—the production and deployment of clean power technology. A counterforce to overspecialization in the techno-science is 'specialization in the context' (Beck, 1992: 158) or studying and understanding the practical implications of technologies in order to reduce risks associated with them. To transpose this idea to the subject of this section, would imply more knowledgeability of photovoltaic module engineers and installers about the ways in which problematic components of end-of-life photovoltaic modules are treated.

With specialization which warrants the delegation of authority to handle end-of-life PV waste to other actors, and at the same time, justifies unfamiliarity of some of the specialized actors with technicalities of PV waste's problematic aspects, the question of responsibility comes in. I suggest that whether it is a producer or an installer, these stakeholders need to engage more with the end-of-life stage of photovoltaics and any potential health or environmental risks the technology could be posing because these stakeholders bring the same technology into the world together. Furthermore, since these actors belong to an interconnected system, everyone involved is susceptible (Hughes, 1993: 6). Considering from social prism, such 'systemic interdependence' (Beck, 1992: 32) implies that when it comes to the management of solar technology's waste risks, all of the involved are responsible. Since the 'general complicity' (ibid: 33) of everyone obscures lines between who is the cause and who is the effect, everyone involved should share responsibility rather than pass the 'hot potato' (ibid: 33). Taking responsibility could mean nothing less than the collaboration of producers with recyclers, gaining a better understanding of end-of-life management of PV modules and as a result, attuning technology production, deployment, or decommissioning practices to the practices of those who treat this technology at the end of the pipe.

4. 6. Temporal distribution of end-of-life photovoltaic waste risks

Risks are about the future (Beck, 1992). Even though they point towards threats that have not yet occurred, these threats are also foreseeable today which also means that risks are real in the present, and call for preventive actions against the crises of tomorrow (Beck, 1992: 33). Following the theme of the temporality of risks, the future occupies a considerable part of informants' accounts in my research. They anticipate that the question of photovoltaic waste management will be resolved once PV waste volumes will increase after the first wave of depreciated solar modules reaches the recycling facilities by 2029 in Austria. A shared notion among my interviewees is that the accumulation of decommissioned photovoltaic panels will turn them into a resource which will create a PV waste market and drive the development of PV recycling technologies. Some of the existing research that has informed my thesis follows this exact logic. These studies reframe the risks of solar waste into a market and technological opportunity, putting forward the projection that more solar waste is key to its effective management (Weckend, et. at., 2016, Dobra and Wellacher, 2019).

This approach where any type of waste is seen as inefficiency, therefore a resource that can be redirected back into the production and ultimately, the market, complies with the notion of circular economy, a popular concept among EU policymakers (Alexander and Reno, 2020). It posits that the negative use-value of waste can become positive, and material use together with the energy use can be minimized through product life-span prolongation, reuse and recycling (Cooper, 2016). The concept rejects the traditional linear model of market economy and the assumption that the earth has an infinite supply of raw materials or an unlimited waste-absorbing capacity (ibid). While the idea of circular economy is borrowed from small-scale natural ecologies, believing that waste can be eliminated altogether '…if waste-producing locales and processes' are 'properly aligned…' (Alexander and Reno, 2020:7), the problem is that in the contemporary socio-economic context, this alignment would be guided by market rules, hence solutions would depend on profitability. In light of such context, it is telling when a PV technology expert articulates the current state of PV waste recycling in the following manner:

'*…there are not enough of them [end-of-life PV's] to make big money out of. You cannot earn something with a few cents per container because there are not enough containers of PV waste'* (Informant 1, Nov. 16, 2020)

While present-day shortage in solar waste is the reason why PV recycling is still an underdeveloped industry according to the research informants, the future looks different for them. The silicon crystalline panel producer believes that their plant '*will have finished recycling solution*…' by 2029. Others such as a solar module developer describes future PV module separation technology by highlighting that efficient removal and sorting of PV module materials like plastic, metal, and silicon will be standardized:

'*…the recycling is on the way to do this in the future…why in the future? Because in the future you have a lot of modules and then the recycling will become more lucrative'* (Informant 5, Apr. 16, 2021).

Another solar technology developer emphasizes the role of higher end-of-life PV waste volumes that are going to rectify currently flawed recycling practices and on the example of a real-life case, points towards what lies ahead:

'There is a company in Germany which developed a very specific approach in recycling. They have thought it through, like separation of materials, especially in the chemical treatment and regaining silicon and the metals and finding the use for polymers. Their problem is—we have talked a lot to the founder of the company in the last three years—that he does not get enough PV modules to operate his plants properly and that is right now the issue but this, I think, will change in the next years very suddenly' (Informant 3, Dec. 1, 2020).

That more end-of-life solar waste is better for its reduction and hazard management is premised on the economic value of waste materials (Dale, et. al, 2017: 167). The recycling industry is the embodiment of this approach but the rub is that in the context of PV waste, the profit and market primacy approach locks environmental risk reduction in as a subordinate matter, thus perpetuates current production forms and nature-society relations. Besides, the delegation of solar waste risk reduction to the future, in anticipation of technological solutions, manifests thinking within the paradigmatic boundaries of modernization where techno-scientific progress and economic growth is what drives society forward in time (Jasanoff, et. al., 2001) but underestimates new and unknown risks that threaten the same progress (Beck, 1992), or overlooks material and energy limitations that make continuous march forward to infinite growth impossible (Dale, et. al, 2017). Furthermore, even if Austria's recycling sector manages to resolve end-of-life PV treatment issues such as material agency, use of chemical inputs in recycling, and energy intensity of PV waste processing, other challenges including photovoltaic production waste and its socio-environmental risks are likely to remain.

4. 7. Spatial distribution of photovoltaic waste risks

If we expand the definition of solar waste to the entire life-cycle of photovoltaic technology and consider it from the political ecology perspective, we get a complex picture. Improved PV recycling technologies would indeed be a great advancement for PV waste-related environmental risk mitigation at the local scale but this would not suffice in addressing the dependence of the Austrian photovoltaic production industry on the global photovoltaic market and global supply chains where the circulation of cheaper technology is encouraged. Cheap things, on the other hand, imply cheap human work and exploited nature (Patel & Moore, 2017). Put it otherwise, the Austrian PV industry's interlinkages with other geographies and markets with lax environmental and labor codes make management of upstream photovoltaic waste unfeasible. Moreover, when considered that Austria exports its photovoltaic technologies, this means that it also dispatches end-of-pipe socio-environmental risks to those countries where environmental standards are lower and waste-recycling practices are absent. With this argument in mind, it should be noted that Austria exports at least 60%

of its domestically produced solar modules (nachhaltigwirtschaften.at, 2019) including to the Middle East, Asia, Africa and North America (bmwfw.gv.at, 2017). This state of affairs leads us from the *temporal delegation* of PV waste-related risks to the question of the *spatial distribution* of risks, their movement and uneven allocation. Free flow of risks via the global market, further elevates the role of supply chains and complicates solar waste risk management in a socially and environmentally just manner.

In connection to this, the silicon crystalline module producer shares that finding '*deliverers as near as possible*' for solar panels is the company's priority but finding all necessary materials within Europe has become impossible in recent years. According to the producer and other informants of my research, the European photovoltaic industry experienced a crisis from 2010 until 2016. This collapse, linked to the rise of Asian producers, '*killed*' Europe's photovoltaic production sector, including in Germany which was and still remains the leader on the European photovoltaic market:

> *'For the moment, we have no solar cell producer in Europe…maybe, two or three small producers who only produce for their own [needs]…so when we want to have solar cells in our modules...they [have to come] from China and from Taiwan…we get our EVA sheet from China because our last European producer left two years ago…until last year, we sourced junction box from Czech Republic but the producer stopped and we had to switch to China…'* (Informant 6, May 4, 2021)

He explains that before the European PV industry's collapse, Austria was self-sufficient and supply chains were mostly local:

> *'…we had 60 to 70 percent of all value chain in Austria. We had cell producer in Austria, we had a backsheet producer in Austria, derivant producer of course and the rest was sourced in neighbor states from Germany…so we sourced everything within Europe until 2011-2012'* (Informant 6, May 4, 2021)

What this informant's accounts suggest among other things is that risks that relate to solar waste, do not travel similar to other electronic waste in a commonly, and as argued, inaccurately perceived single-direction—from rich countries of global north to poorer countries of global south alone (Lepawsky, 2015). Risks make their way into countries of the global north and Austria too through imported photovoltaic components. However, these risks are different in nature, and magnitude. For instance, when we consider risks from PV component import, they have more of socio-economic implications for those social groups in Austria who once depended on the local photovoltaic production. On the other hand, countries with looser environmental and labor regulations where photovoltaic components are produced to feed Austrian solar industry, endure heavier environmental burden from PV production waste and its hazards. As for end-of-life PV waste, while it is recycled in Austria, suggesting lesser environmental risks locally, for countries with under-regulated electronic waste management system, imported photovoltaic technology from Austrian producers can mean pollution of ecosystems from landfilled broken-down PV modules (Mulvaney, 2019).

To return to the matter of supply chains, how they are linked to waste might not be so obvious at first but they combine production waste, transportation waste—in the form of carbon emissions—and eventually, end-of-life PV waste together with recycling waste. Global photovoltaic supply chains transcend borders, hence they transmit socio-environmental risks spatially and across scales, meaning that supply chains add to waterways, soil and air that conduct solar waste hazards beyond borders. Another problem is that through long supply chains, solar waste risks become 'incalculable' (Beck, 1992: 22), as they get harder to contain or control and produce 'social risk positions' (ibid: 23) for those who inhabit less protected, therefore more afflicted localities. Thus they make solar waste hazards not only specific but in a way, 'universal', and importantly, 'unpredictable' (ibid: 27) source of socio-environmental risks.

Considering all the above, it is legitimate to assume that shortening of supply chains is crucial for the mitigation of socio-environmental risks of solar waste. The interviewed solar module producer suggests the same and makes optimistic prognosis about the return of photovoltaic technology production to Europe. He relates this change to new political initiatives such as European Green Deal which targets new environmental goals and supports the increase of renewable energy technology funding. He adds that:

> *'…all producers left in Europe are actually investing in new production capacity and when you have more producers, then maybe, also the supply chain can pick up in Europe.'* (Informant 6, May 4, 2021)

While the potential for shortening supply chains is undeniably good news for Austrian photovoltaic producers, and can improve the country's carbon footprint from photovoltaic technology, other risks, such as export of polluting toxicants to other geographies through locally produced panels, as well as unresolved aspects of recycling remain up in the air, with the latter being delegated to the future techno-scientific innovations and economic profitability of scaled-up PV waste.

Conclusion

This thesis explored the perspectives of photovoltaic technology experts and solar industry's key stakeholders on socio-environmental risks of photovoltaic waste in Austria. By examining the case from political ecology lens, I have situated Austria in the global context and considered photovoltaic technology's supply chains to argue about multidirectional, yet uneven spatial distribution of socio-environmental risks associated with photovoltaic waste. It must be noted that even though, the end-of-life photovoltaic modules have featured as a central subject in my analysis, I have used the broader definition of waste and touched upon the implications of PV production waste and supply chains as well.

Through the accounts of the study participants, I have shown that despite their green credentials, and their undisputable advantages in carbon-free electricity production, photovoltaic panels carry environmental risks when their materiality and full lifecycle is considered, and this applies to Austrian context as well. Even in the conditions of national and the EU level waste management regulations that organize decommissioned photovoltaic waste treatment in Austria, some issues remain unresolved. For example, if we start from the end of photovoltaic lifecycle, the interviews have suggested that the recycling of most common and the cleanest of photovoltaic modules from the point of material composition—crystalline silicon photovoltaics—require the use of additional chemical inputs for material recovery, or contain hard-to-recycle components, challenging the underlying green principles the recycling and photovoltaic technology itself are meant to ensure. Similarly, the energy-intensity of the end-of-life PV recycling persists as an unaddressed issue. It has also become clear that photovoltaic waste might create risks of overwhelming Austria's existing recycling infrastructure with the inevitable increase of its streams, unless thorough systemic adaptations are carried out along the chain of photovoltaic waste management.

More to the point of anthropological subject of discussion, I have shown that the ways in which key stakeholders and photovoltaic technology experts reflect on PV waste or its environmental risks in Austria, is delegated not only to specialized waste management entities but temporally, to the future as well. Notably, the current insufficiency of PV waste volumes is viewed as the major impediment to the improvement of PV waste treatment and subsequent elimination of environmental risks. On the other hand, the future is seen as a temporal dimension where more PV waste is going to create the new market and profit opportunities—conditions on which development of PV waste treatment technologies, therefore reduction of pollution or other environmentally harmful risks depends. I argue that this mode of thinking is a blend of economic growth rationality and environmental consciousness which underpins the logic of green growth and circular economy (Dale, et. al., 2017). In the technology-driven green growth paradigm nature is economized and features as 'a type of capital' (ibid: 2). For its apolitical approaches to 'systemic contradictions' (ibid: 6) and for believing that socio-ecological crises can be addressed by technological innovations primarily, green growth attracts criticism (Dale, et. al., 2017). Considering the caveats of this economic model, I maintain that tying PV waste and its treatment technologies to growth principles means economization of environmental risks, therefore entrusting their elimination to profitability which once again, subverts the green license of photovoltaics.

In addition, I have observed that the lack of knowledge among some photovoltaic engineers and producers about how problematic end-of-life photovoltaic waste components are treated, has highlighted the importance of shared responsibility in risk management and the need for the increased cooperation of specialized experts across photovoltaic technology's lifecycle with each other and with recyclers.

Lastly, by situating Austria in global market relations and linking it to global supply chains in correspondence with the political ecology approach, I argue that PV waste risks, move from and to Austria, albeit affect it to a much lesser degree than some of those localities where environmental, electronic waste management and labor standards are lower but where Austria sources its components from or exports locally produced modules to. I also contend that the movement of these risks through supply chains and the global photovoltaic technology market make them uncontainable. Furthermore, the diminished local PV component production in Austria implies that social and even economic risk positions are produced for those communities that once relied on the local solar industry. However, this has to be demonstrated through research and could potentially be a productive site for future studies. In addition, long supply chains of solar module components that feed the Austrian solar industry, increase the carbon footprint of locally manufactured photovoltaic technologies, producing a more global negative environmental impact.

Relying on the accounts of its informants, this thesis suggests that addressing existing challenges in PV recycling might enable Austria to resolve the end-of-life question of photovoltaic waste question locally but socio-environmental risk management from PV production waste and supply chains will remain beyond its control. The localization of supply chains could change this status quo but major shifts would be necessary to this end. Namely, the transformation of photovoltaic market relations at broader, regional or even global scale and enforcement of global PV waste management regulations together with coordinated efforts of suppliers and producers for the reduction of PV production waste, therefore minimization of any negative socio-environmental impact from the lifecycle of photovoltaic technology. These shifts, however would require not only technological advancements but political decisions as well. In other words, not just the politicization of solar power would suffice in Austria but the politicization of photovoltaic waste would be necessary as well. This would contribute to the creation of an environmentally safer material infrastructure for solar power expansion and overall, a more socio-environmentally just solar expansion process in Austria.

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Appendix 1

	STAKEHOLDER	INTERVIEWEE
1	A major Austrian technology research and development institute	Senior Scientist specializing in energy and photovoltaic technology
2	A waste processing technology institute	Leading expert in waste management and photovoltaic technology recycling
3	A company specializing in polymer and solar cell research	Manager, engineer
4	An thin film solar module production company	Head of production development
5	Technology innovation laboratory specializing in photovoltaics	Engineer
6	A silicon crystalline photovoltaic module manufacturer	Head of product management, engineer
7	A major electronic waste collection and processing service provider	A legal expert, specializing in regulations on photovoltaic waste management
8	Association of photovoltaic technology lobbyists and various interest groups	Expert
9	Austrian energy provider and photovoltaic module installer	Expert
10	An urban innovation center	Renewable energy expert

Appendix 2

INTERVIEW GUIDE

PHOTOVOLTAIC TECHNOLOGY

1. What makes photovoltaic technology attractive in general and in Austrian context specifically?

2. How has photovoltaic sector changed in Austria in recent years?

PV WASTE

3. What would you tell us about PV waste and how is this issue dealt with in Austrian solar industry?

4. How would you evaluate the presence of photovoltaic waste in public discourse in Austria as opposed to the adoption of solar power technology?

5. How could current recycling practices change in Austria with the growth of end-of-life photovoltaic waste streams?

REGULATION

6. How do you think photovoltaic modules are similar or different to e-waste? Should PV's be the subject of the same regulation as other types of electronic waste and how comprehensive is WEEE directive for end-of-life treatment of photovoltaics?

MATERIALS

7. How much does PV technology improve in terms of material sustainability and safety?

8. What happens to unrecyclable PV components? What materials are they made of?

GLOBAL CONTEXT

9. In what ways is Austrian photovoltaic sector connected to the global photovoltaic market and how does this affect local market?

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