Research-Thesis: Are Renewable Energy Supply Chains Sustainable? A Triple Bottom Line Assessment Across the Full Lifecycle.

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Diplôme : Master en sciences de gestion, à finalité spécialisée en global supply chain management
Année académique : 2025-2026
URI/URL : http://hdl.handle.net/2268.2/25735

Are Renewable Energy Supply Chains Sustainable?

A Triple Bottom Line Assessment Across the Full Lifecycle

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To obtain the degree of
MASTER IN MANAGEMENT
with a specialization in Global
Supply Chain management.
Academic year 2025/2026

Ecole de Gestion de l'Université de Liège

“Not everything that glitters is gold.”

William Shakespeare, The Merchant of Venice.

Acknowledgements

This thesis would not have been possible without the support and guidance of several people to whom I owe my deepest gratitude.

First of all, I would like to thank my supervisor, Professor Jérôme De Boeck, for his availability, his thoughtful feedback, and his trust in the direction this research took. His questions pushed me to think more deeply and his guidance helped me build an argument I am genuinely proud of.

I would also like to express my sincere gratitude to the former Head of Electrical Department at NOMAC, who agreed to share his experience and insights about the NOOR Ouarzazate Solar Power Station. His perspective from inside one of the world's largest solar projects gave this research a human dimension.

I would also like to thank my colleagues at Ferrero Luxembourg for their support and encouragement during my internship, which ran alongside the writing of this thesis. Their kindness and generosity made what could have been an overwhelming period much more manageable.

Finally, I want to thank my family especially my mother and my friends for their patience and encouragement throughout this journey. Writing a thesis is rarely a solitary exercise, and their support made all the difference during the most demanding moments.

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Abbreviations

RE: Renewable energy
SSCM: Sustainable Supply Chain Management
TBL: Triple Bottom Line
HHI: Herfindahl-Hirschman Index
PV: Photovoltaic
GDPR: General Data Protection Regulation

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Introduction

The transition towards renewable energy is widely recognized as one of the primary solutions to climate change and the reduction of greenhouse gas emissions at a global scale. Driven by international agreements such as the Paris accord of 2015, the deployment of solar photovoltaic and wind energy technologies has accelerated significantly recently. However, behind this remarkable growth lies a more complex reality that is rarely discussed.

Renewable energy is usually described as being "clean", "green" and "sustainable". Yet, this research argues that such labeling is often premature and, in many cases, misleading. Evaluating sustainability of RE only at the point of generation hides a much bigger picture, the one where serious environmental, economic and social problems exist at every step of the chain. This selective framing reveals what this research called a "Sustainability Paradox", showing that the very technologies designed to reduce emissions are actually produced through carbon-based processes, in geographically concentrated regions, through supply chains that generate their own sustainability challenges.

Reaching the green target "Net-zero emissions" by 2050 requires multiplying solar and wind installations at a speed never seen before. But this rapid growth comes with a cost. From mining the raw materials to disposing of used equipment, every step of the supply chain creates environmental, economic and social issues that are often ignored. On top of that, the race for green energy has increased the demand for critical minerals, pushed mining to its limits and made the entire system dependent on a very small number of countries for the main components. However, none of this stops companies and governments from calling renewable energy sustainable, often using the label as a selling point rather than a verified claim.

It is from these observations that this research builds its central question: are renewable energy supply chains sustainable when environmental, economic, and social dimensions are considered across their full lifecycle, and to answer this question, the study combines a quantitative analysis of supply chain indicators, a perception survey, and a case study of the NOOR Ouarzazate Solar Power Station in Morocco.

Chapter 1 : Literature Review

1.1 Renewable Energy Supply Chain (RESC)

Before evaluating whether renewable energy supply chains are sustainable, it is essential to first understand what they actually are and how they work. Renewable energy, at its simplest level, refers to energy collected from resources that naturally replenish themselves, such as sunlight, wind, and water. Jelti et al. (2021) define the Renewable Energy Supply Chain as the process of transforming natural energy sources into electricity that can be used for everyday use and what makes this chain unique is that it depends mainly on materials and equipment rather than on coal which is unlike the fossil fuel power plants, where energy is produced through the continuous burning of coal or gas. So, R.E systems have a free and inexhaustible fuel. However, what appears simple at the generation level becomes more complex when considering the full chain.

As Mertens et al. (2024) explain, producing solar panels and wind turbines requires significant quantities of critical raw materials like lithium, cobalt, silicon and rare earth elements. These materials must be extracted, refined, manufactured and transported, each of these steps forms a stage of supply chain, and each stage hides its own set of impacts that exceed the simple act of generating electricity.

Hmouda et al. (2024) reinforce this point by arguing that sustainable supply chain management in energy production can be achieved only if we consider all its phases at the same time, not stage by stage in isolation. In other words, what happens at the mining stage affects what happens at the manufacturing one which in turn affects logistics, installation until the last phase of the chain. By this we can say that "the Chain is one connected system".

1.2 Definition of Sustainability

The perspective mentioned earlier is what this research adopts, and to build it properly, we have to step back and ask a more important question: what does sustainability mean? A question that may seem obvious, but in practice, the concept is used in so many different ways and applied to so many different contexts. This research will gradually show, the way this concept is defined and measured matters enormously when evaluating renewable energy systems.

The most accepted definition of sustainability comes from the Brundtland Report (1987) that defines it as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." This definition places sustainability at the intersection of time, showing that what we do today must not damage what tomorrow will need. Although this definition is wide, it established the foundation for what after become known as the Triple Bottom Line (TBL) framework.

Elkington (1997) formalized this framework by arguing that true sustainability requires a transition in how organizations evaluate their performance. As illustrated in his work "Cannibals with Forks" the old paradigm focused exclusively on the financial bottom line by measuring success purely in economic terms. The new paradigm he proposed replaces this measure with a Triple Bottom Line that integrates three dimensions at once: economic, social, and environmental and this was not simply an academic proposal, it was a call for a complete reconfiguration of how value, impact, and responsibility are understood across industries and supply chains.

Seuring and Müller (2008) later applied this framework specifically to supply chain management, arguing that sustainable supply chains can only be achieved when all three dimensions are considered across every stage of operations. This definition is important because it makes clear that sustainability in supply chains is not a choice between dimensions, all three must be pursued and evaluated together, across every stage of the chain.

This is exactly where the challenge begins for RE. As Hmouda et al. (2024) observe, sustainability in energy production is rarely evaluated through all three lenses. Environmental issues dominate the research, appearing in 77 out of 97 papers, while the social dimension has attracted the lowest interest with only 30 papers. The focus is precisely on the environmental dimension and even then, only on the operational phase, the moment when electricity is generated. The economic and social dimensions, as well as the upstream and downstream stages of the supply chain remain in the background. So, when only one dimension is measured, and only at one stage of the lifecycle, the full picture is incomplete, and an incomplete picture can lead to conclusions that sound reassuring but may not fully reflect reality.

1.2.1 Environmental Dimension

The environmental dimension is the most discussed aspect of renewable energy sustainability in the academic literature and the one on which the case for renewable energy is the strongest. Renewable energy technologies generate electricity without direct carbon emissions during operation, making them different from fossil fuel systems where every unit of energy produced releases greenhouse gases into the atmosphere.

Owusu and Asumadu-Sarkodie (2016) conducted one of the most detailed studies on the environmental opportunities of renewable energy by concluding that renewable technologies are sustainable based on current and future economic and social needs, identifying four principal environmental benefits: reduced greenhouse gas emissions, climate change mitigation, lower environmental and health impacts and in their view, moving away from fossil fuels toward renewable energy is not optional, it is the most realistic path to reducing greenhouse gas emissions and addressing climate change.

Mertens et al. (2024) share this positive opinion while introducing what they call the "From Emissions to Resources" challenge. They acknowledge that the transition to renewable energy creates an important increase in demand for critical raw materials representing a new form of resource dependency that did not exist with fossil fuel systems. They note that having access to these materials in what they describe as a "sustainable" way requires addressing the environmental and social impacts of mining, the dominance of China in material processing and manufacturing, and the geopolitical challenges this creates. However, Mertens et al. (2024) do not see these challenges as reasons to question the environmental aspect for renewable energy, instead, they argue that through a combination of solutions using for example materials more efficiently, finding substitutes, improving recycling, and diversifying production, the critical raw material problem can be reduced, allowing the energy transition to continue toward its climate goals.

Besides the upstream stage, the end-of-life phase of renewable energy systems presents its own environmental considerations. Sharma et al. (2024) argue that the end-of-life management of solar PV panels is an emerging challenge that the sector is beginning to address, noting that recycling PV panels can reduce environmental impact by up to 70% compared to landfilling, and that recovered materials such as aluminium, glass, copper, and silicon can be reused in the manufacturing process, contributing to a more circular supply chain.

The literature therefore builds its environmental case for renewable energy mainly around the generation phase where emissions are near zero which is reflected in the research: according to Hmouda et al. (2024), the attention always goes to the environmental considerations and the stages that precede electricity generation receive considerably less attention.

1.2.2 Economic Dimension

Alongside its environmental benefits, renewable energy is increasingly presented in the literature as an economically attractive alternative to fossil fuels. Owusu and Asumadu-Sarkodie (2016) identify economic development as one of the opportunities associated with renewable energy by showing that the sector creates jobs, attracts investment, and reduces the dependence of the country on imported fossil fuels which bring an economic benefit for countries that adopt it. In their view, the economic opportunities of renewable energy go far from the simple cost of electricity to include a broader advantage that fossil fuel systems, with their dependency on imported fuels and unpredictable prices, cannot offer in the same way.

Seuring and Müller (2008) provide the theoretical foundation for assessing economic sustainability in supply chains. According to them, the economic sustainability requires that all stages of the chain remain financially practical, resilient, and capable of absorbing disruptions over the long term which is important because it extends the economic assessment of renewable energy beyond the cost of generating electricity which has fallen dramatically in recent years, to include the financial stability of every stage of the supply chain, from raw material sourcing and manufacturing to logistics, installation, and end of life management. A system that is economically competitive at the generation phase but financially fragile at earlier stages cannot be considered economically sustainable in the full sense that Seuring and Müller (2008) describe.

Mertens et al. (2024) bring this supply chain perspective to the economic dimension of renewable energy by highlighting the risks created by the concentration of critical raw material processing in China by warning that this dependency exposes the entire industry to political tensions between countries, for example, if relations between China and the rest of the world deteriorate, the supply of materials that renewable energy depends on could be disrupted. This is not a hypothetical risk; it is a weakness built into how the global renewable energy supply chain is currently organized.

Hmouda et al. (2024) confirm that the economic dimension is the second most researched pillar in sustainable energy supply chain literature, behind the environmental dimension. However, they note that economic research in this field focus more on the cost competitiveness and investment flows rather than on the financial resilience of the full supply chain leaving significant gaps in how the economic sustainability of renewable energy is understood and evaluated across all its stages.

1.2.3 Social Dimension

Of the three dimensions of sustainability, the social one is the least explored and discussed in the context of renewable energy sector. This is not because social issues are absent from the supply chain, it is because they are harder to measure, less visible, and less politically convenient to discuss. Hmouda et al. (2024) found that out of 97 papers reviewed on sustainable supply chain management in energy production, only 30 addressed the social dimension making it by far the most neglected pillar of the three.

The social arguments in favor of renewable energy mainly around job creation and energy access. Jelti et al. (2021) define the energy transition as an opportunity for social and economic development, mentioning job creation as one of the most tangible social contributions of renewable energy supply chains. Owusu and Asumadu-Sarkodie (2016) go further, identifying social and economic development as one of the four principal opportunities of renewable energy, added to energy security, energy access, and climate change mitigation. In their view, communities that adopt renewable energy stand to gain not only cleaner electricity but also new employment, improved health outcomes, and greater energy independence.

Seuring and Müller (2008) provide the theoretical grounding for what social sustainability actually requires in a supply chain context. They argue that social criteria must be fulfilled with environmental and economic ones meaning that a supply chain cannot be called socially sustainable if it gives us benefits at one end while creating harm at the other. This definition is important because it switches the question from whether renewable energy creates social benefits, which it does, to whether those benefits are distributed fairly across the full chain.

It is on this point that Mertens et al. (2024) introduce a perspective that the broader literature keeps avoiding. They acknowledge that mining activities for the critical raw materials that renewable energy requires often take place in regions where labor conditions and human health impacts are not given adequate attention. In their words, a continued and increased focus should be placed on the social impact of these upstream activities, a call that reflects an awareness, even authors who strongly believe and support renewable energy transition acknowledge that the social picture is more complicated than simply counting the jobs it creates.

1.3 Sustainable Supply Chain Management: Concepts and Challenges

Supply chain management has been developed considerably over the past decades. Before, it was focused on efficiency, cost reduction and speed, however, today, it is progressively expanding to incorporate a broader set of responsibilities. Seuring and Müller (2008) define SSCM as the management of material, information, and capital flows across the entire chain while taking into consideration goals from all three dimensions of sustainable development. This definition places the responsibility for sustainability not only on individual companies but on the entire network of actors that together form the supply chain. Besides, it is significant in the context of global supply chains, where production processes are dispersed across multiple countries and continents, and where the environmental and social consequences of upstream activities are often invisible to the final consumer.

In the energy sector precisely, Hmouda et al. (2024) argue that this approach to SSCM remains underdeveloped. Their article reveals that research in this field is scarce, unbalanced, and focused on single energy sources such as biomass, whereas solar and wind energy supply chains are rarely discussed, creating a striking gap given that solar and wind are the two technologies at the heart of the global energy transition.

Understanding and managing these challenges properly requires a clear and honest framework that evaluates the full chain, not just the parts that are easy to measure.

1.4 Research Gaps

The literature reviewed in this chapter covers the structure of renewable energy supply chains, sustainability concepts and the challenges identified at each stage, but besides what the authors explicitly say, a closer reading also reveals something less visible, a set of patterns and tensions that this research believes deserve more attention.

A close observation across the reviewed literature is the use of terms such as "clean", "green" and "sustainable" to describe renewable energy technologies. These labels appear consistently and almost without question, yet the same studies that use them also document significant environmental damage during extraction, economic risks linked to supply concentration, and social impacts in mining regions. The gap between the words used and the realities described is rarely acknowledged and it is precisely this gap that this research aims to examine. The biggest question this raises is: when researchers call renewable energy sustainable, what exactly are they measuring? In most cases, the answer is the generation phase where electricity is produced without emissions. But a supply chain does not start and end there, it begins in a mine and ends in a waste facility, and everything that happens in between matters too. The literature usually focus on where renewable energy looks best, and this creates a picture that is real but incomplete. From a supply chain management perspective, an evaluation that excludes large portions of the chain is not a full evaluation it is actually a partial one dressed as a conclusion.

On top of that, sustainability has three dimensions but they are not given equal attention across the literature. Environmental considerations dominate the research while economic and social impacts, especially those happening upstream in extraction and manufacturing, are often neglected and treated as secondary. Besides, the Triple Bottom Line framework, which the literature itself relies on to define sustainability, is explicit: all three dimensions must be considered together, therefore, a system cannot be called fully sustainable when only part of it has been properly examined.

Finally, there is a question that the literature has underrepresented: how do people actually understand sustainability when it comes to renewable energy? What does the word mean to them, to professionals and the general public who consume and support this transition every day? This matters because public understanding drives policy decisions, investment choices, and the social acceptance of the energy transition and it has barely been studied from a supply chain perspective. Then, if the gap between how sustainability is claimed and how it is actually understood is wide, then the energy transition may be moving forward on a belief that has never been properly verified.

1.5 The Sustainability Label: Between Communication and Reality:

These gaps in how sustainability is measured and reported raise a broader question: how did an incomplete picture come to be accepted by a large audience, and what mechanisms allowed it to be communicated as if it were complete?

Saying that something is sustainable and actually proving it are two very different things, and this difference has become an increasingly important topic in academic research. Over the years, as sustainability became a popular concept in business and politics, many organizations started using the word without necessarily changing the way they operate because calling a product or a service sustainable became a way to attract customers, investors, and positive attention, even when the evidence behind the claim was incomplete or selective. Senyapar (2024) calls this greenwashing, and describes it as a practice where companies present themselves as environmentally responsible without making the real contributions and changes needed to justify that image and this by exposing only the positive aspects of what they do while staying silent about the negative ones, using strategies that include making broad environmental claims without providing evidence, sharing only the data that looks good while hiding less favorable information, and focusing on small improvements while ignoring more serious problems that exist elsewhere in their operations.

What makes this effective is the way sustainability is communicated to the public. Senyapar (2024) shows that companies use green labels, eco-friendly packaging, and carefully designed marketing campaigns to shape how their products and services are perceived, and that the rise of social media and digital marketing has made the way much easier to reach vast audiences very quickly and with very little resistance. Because environmental topics are technically complex and most people do not have the expertise to evaluate sustainability claims in depth, organizations can present a partial picture as if it were complete and the public, exposed repeatedly to the same green messaging without access to the full supply chain reality, gradually internalizes the idea that the products and sectors carrying these labels are genuinely sustainable, even when they have never been verified as such.

Elkington (1997), who introduced the Triple Bottom Line framework, had already anticipated this risk, he understood that organizations could start using the language of sustainability without actually committing to what it requires, and that as sustainability became more and more associated with a good reputation and commercial success, more organizations would claim it than would genuinely pursue it.

Seuring and Müller (2008) bring this concern specifically to the supply chain context, arguing that sustainability claims are often made at the level of the most visible part of the operation without examining what happens at earlier and later stages of the chain, which means a product can carry a sustainable label based on how it performs at one stage while the supply chain that produced it remains completely unexamined and in global supply chains where upstream activities take place far away from where the final product is consumed, this kind of selective labeling is easy to maintain and very difficult for anyone outside the chain to question.

What this means for this research is that the question being asked is not simply whether renewable energy has environmental, economic, and social benefits because the literature reviewed in the previous sections shows that it does but whether the sustainability label applied to it reflects a complete and honest assessment of the full supply chain, or a selective one built around the stages where its performance is

strongest, and it is precisely this question that the analysis, case study, and survey chapters of this research set out to answer.

Chapter 2 : Methodology

2.1 Research Design:

The central research question of this study cannot be answered through numbers alone or through description alone. To assess whether renewable energy supply chains are sustainable when considering the three dimensions across their full lifecycle, the research needed to both measure what is happening in the supply chain and understand what it means in practice for a real project and for the people who ultimately use the electricity it produces. For this reason, a mixed methodology was adopted, combining quantitative analysis based on institutional data and statistical evidence with qualitative analysis based on document triangulation, an expert interview, and the open responses collected through a perception survey. The two approaches work together rather than separately because the quantitative evidence establishes the patterns and the qualitative evidence helps explain what those patterns mean in reality.

2.2 Research Database:

Two databases were built and organized for this research with different purposes to be served by each one.

The first covers the global renewable energy supply chain and contains 94 quantitative indicators compiled from eight institutional sources: *IRENA Renewable Power Generation Costs (2024), IRENA Renewable Energy Jobs Annual Review (2024), IEA Solar PV Global Supply Chains (2022), GWEC and BCG Mission Critical Wind Supply Chain Report (2023), NSEFI Solar PV Manufacturing in India (2023), EBRD Wind Supply Chain Report (2024), USGS Mineral Commodity Summaries (2024), and IPCC Fifth Assessment Report (2014).* These sources were chosen because they are among the most credible and comprehensive institutional sources available on renewable energy supply chains, and together they cover all four stages of the chain: upstream, midstream, operation, and end of life. Every indicator was classified by TBL dimension and by supply chain stage so that the analysis could move systematically across the full lifecycle. The distribution of indicators is asymmetric: 77 economic (82%), 12 environmental (13%), and 5 social (5%) and this imbalance is itself a finding rather than a methodological weakness, as it reflects how little social data exists in institutional sustainability reporting, consistent with what Hmouda et al. (2024) found in their review.

The second database is dedicated to the NOOR Ouarzazate case study and contains 65 data points from the MASEN Environmental and Social Impact Assessment (FESIA, 2014), the World Bank Implementation Completion and Results Report (2025), the African Development Bank Project Completion Report, and the academic study by Laaroussi (2023). These data points are complemented by an expert interview conducted in March 2026 with a former Head of Electrical Department at NOMAC, the company responsible for operating the NOOR complex, who agreed to share his operational perspective on the project. The interview focused on the operational performance of the plant, the environmental considerations actually monitored in practice, and the supply chain dependencies behind the project's components.

2.3 Analytical Approach

The approach of this research is based on the Triple Bottom Line as introduced by Elkington (1997) and applied to supply chain management by Seuring and Müller (2008). For the global supply chain analysis, the renewable energy supply chain is examined in four sequential stages: upstream extraction, midstream manufacturing, operation, and end of life and at each stage the indicators are assessed at the same time through the environmental, economic, and social dimensions.

At the end of each stage, a scoring framework is applied: 0 means the stage fails on a given dimension, 1 means it partially meets the sustainability criteria because the data shows a real progress but the stage still face problems that prevent a full score, and 2 means it fully meets them, giving a maximum possible score of 6 per stage. This three-level approach was chosen because it reflects the three possible outcomes that the Triple Bottom Line framework produces and there is no need for more detailed levels when the framework itself only distinguishes between failure, partial compliance, and full compliance.

The three TBL dimensions are treated as equally important in this scoring framework, reflecting the Brundtland (1987) definition which does not prioritize any single dimension over another.

One clarification is needed for the social dimension specifically. A score of 0 is assigned either when social conditions are clearly poor or when no social data exists to make a judgment at all. A score of 1 is assigned when social problems exist but are limited to specific locations rather than being spread across the entire stage. A score of 2 is assigned when social criteria are genuinely met by all the main actors involved in that stage.

To assess how geographically concentrated renewable energy supply chains are, the dominant country's market share is identified for each critical material and component, and these shares are averaged within each stage to produce an overall concentration level. All materials are treated equally in this calculation not because they are all equally critical to the supply chain, but because the main finding is that concentration is high everywhere, and this conclusion holds regardless of how the materials are weighted.

For the NOOR case study, the analytical approach shifts from quantitative aggregation to qualitative triangulation. The sustainability claims made in the official MASEN project documents are compared against three independent sources: the World Bank completion report, Laaroussi (2023), and the expert interview and each testable claim is classified as confirmed, contradicted, partially supported, or omitted. This triangulation matrix forms the analytical backbone of Chapter 4.

2.4 Perception Survey:

Numbers and case studies can show what is wrong with renewable energy supply chains but they cannot show whether the public knows about it. To fill this gap, a short perception survey of 11 questions was designed and distributed to both professionals and the general public, taking approximately four minutes to complete.

The survey follows a before and after structure where respondents first rate the sustainability of renewable energy and indicate what they associate with the concept, then read three factual statements about the upstream and end of life stages of the supply chain, and finally rate sustainability again. The difference between the two ratings is the core finding of the survey. Two additional questions capture whether respondents inform themselves about sustainability and whether they translate that awareness into action, and two open-ended questions ask what would make renewable energy sustainable and what the most urgent change needed is.

A total of 115 valid responses were collected, exceeding the minimum of 100 required by the Yamane (1967) formula at a 90% confidence level and a 10% margin of error. All statistical analyses were conducted in JASP 0.18 with a significance threshold of $\alpha = 0.05$, and all responses are anonymous and used exclusively for academic purposes in compliance with GDPR regulations.

2.5 Case Study: NOOR Ouarzazate, Morocco

The NOOR Ouarzazate Solar Power Station was chosen as the case study for three reasons. First, it is one of the largest solar energy projects in the world and is located in a developing country, which places it at the intersection of the environmental, economic, and social dimensions of sustainability. Second, because it was financed by international institutions including the World Bank, the European Investment Bank, the African Development Bank, KFW, and AFD, multiple independent evaluation reports are publicly available, making a rigorous triangulation possible in a way that is rarely feasible for projects of this scale. Third, NOOR offers a concrete opportunity to test whether the sustainability challenges identified at the global supply chain level are also visible in a real project.

Chapter 3 : Analysis and Results

3.1 Upstream Supply Chain Analysis: Materials, Concentration and Sustainability:

3.1.1 Resource Intensity and Material Dependency:

Renewable energy technologies are commonly understood as resource-independent systems that use the sun and the wind, which are free and unlimited, and this is accurate once a solar panel or wind turbine is installed and generating electricity, but it does not reflect what happens before that first watt is produced. Unlike fossil fuel systems where resource consumption is spread continuously over decades of operation, renewable energy concentrates its entire material demand at the manufacturing stage, meaning that building these systems requires extracting and processing important quantities of critical minerals whose supply chains hides a significant sustainability challenges.

The data makes this dependency clear and concrete and larger than most people realize. An onshore wind plant requires nine times more mineral inputs than a plant of equivalent capacity powered by gas , and since 2010 this has increased by a further 50% as renewable energy equipment has grown larger and more complex, with solar PV alone accounting for 10% of global silver demand and 40% of global tellurium use, statistics that together show how deeply the clean energy sector has become dependent on global mining markets in a way that is rarely acknowledged when renewable energy is described as sustainable.

What makes this dependency important to examine is not simply its scale but its direction of travel. As global renewable energy capacity has more than doubled since 2015, the total volume of minerals needed each year has grown accordingly, yet developing a new mine takes an average of 16 years from discovery to first production, which means that the mines needed to supply the materials required to meet the 2030 renewable energy targets should have already been identified and developed years ago and in many cases they were not, creating a growing gap between what the energy transition demands and what the upstream supply chain can actually deliver.

3.1.2 Geographical Concentration and Geopolitical Risk:

The material dependency identified in the previous section raises an immediate question: where do these minerals actually come from, and how reliable and secure is their supply? When the upstream concentration data collected in this research is examined as a whole, the answer reveals a level of geographical dependency that goes far beyond what most sustainability assessments of renewable energy acknowledge.

Across the five upstream mineral indicators reviewed in this research database, the average market share controlled by the leading country reaches 83.8%, ranging from 60% to 100% representing a finding that no single institutional source presents explicitly, as it emerges from the analysis of the database constructed for this research. At the individual level, China controls 62% of global rare earth mining and 92% of rare earth processing, while its share of neodymium and dysprosium refining that are both essential for wind turbine magnets, reaches 100% and 88%

respectively, meaning that no alternative source exists for these materials anywhere in the world today. Besides China, the Democratic Republic of Congo supplies 74% of global cobalt, South Africa controls 70% of global platinum, and Ecuador accounts for 90% of global balsa wood exports used in wind turbine blades and then, each country holding a near-monopoly position on a specific material that the energy transition cannot do without.

When these data are read together, what the analysis finds, is a supply chain that has almost no room to absorb disruption. If one of these countries restricts exports, changes trade policy, or faces an internal crisis, the impact travels immediately through the entire renewable energy supply chain with no alternative supplier to turn to. This is not a theoretical risk. Between January 2020 and January 2022, the prices of copper and rare earths tripled, according to the IEA Energy Transition Mineral Price Index and this shows how fragile these supply chains are: when demand grows quickly, the supply cannot keep up because it is concentrated in too few countries.

The energy transition was widely expected to reduce the kind of geopolitical dependency that fossil fuel supply chains have long been criticized for. At the upstream level, however, the data tells a different story: rather than eliminating this dependency, the transition has moved it from oil and gas producing nations to mineral processing countries, with concentration levels that in several cases exceed those of the systems being replaced and with the rules needed to manage these risks are still largely absent.

To formalize this concentration, a Herfindahl-Hirschman Index (HHI) was calculated for nine upstream and midstream components using primary data from USGS Mineral Commodity Summaries 2024 and IEA Solar PV Supply Chains. HHI is computed as the sum of squared market shares (ΣS_i^2), with values above 2,500 indicating high concentration (US DOJ Merger Guidelines). The average HHI across the nine components reached 6,290 that represents 2.51 times the high-concentration threshold confirming that no component of the renewable energy supply chain operates in a competitive market.

Table 1:HHI Concentration level

SOLAR PV						
Polysilicon	China 80%	n/a	n/a	Rest of world 20%	6 800	Highly concentrated
Wafers	China 97%	n/a	n/a	Rest of world 3%	9 418	Highly concentrated
Cells	China 80%	Southeast Asia + Korea 18%	n/a	Rest of world 2%	6 728	Highly concentrated
Modules	China 70%	Vietnam 5%	Malaysia 4%	Others 21%	5 382	Highly concentrated
RAW MATERIALS						
Rare earths (mining)	China 62%	USA 12%	Myanmar 11%	Others 15%	4 334	Highly concentrated
Rare earths (refining)	China 92%	Malaysia 5%	Estonia 1%	Others 2%	8 494	Highly concentrated
Graphite (natural)	China 77%	Madagascar 6%	Mozambique 6%	Others 11%	6 122	Highly concentrated
Lithium (mining)	Australia 51%	Chile 26%	China 15%	Others 8%	3 566	Highly concentrated
Cobalt (mining)	DRC 74%	Indonesia 7%	Russia 4%	Others 15%	5 766	Highly concentrated
Average HHI					**6 290**	**Highly concentrated**

Source: USGS MCS 2024; IEA Solar PV Supply Chains (2022); IEA-PVPS 2024; IEA Critical Minerals Outlook 2024

Formula:

HHI = Σ (market share) ² · >2,500 = highly concentrated · Avg = 6,290 (9 components, all >2,500)

3.1.3 Environmental Consequences of Extraction and Refining:

Mining is the fourth largest driver of global deforestation in the world. This fact alone is rarely associated with renewable energy, yet the two are directly connected. In Ecuador, which supplies 90% of the balsa wood used in wind turbine blades globally, the increase in demand from wind energy manufacturers has led to cutting on lands that belong to local communities and this is not an exceptional case but a reflection of how the environmental costs of renewable energy extraction is concentrated in regions that are geographically and institutionally distant from where the clean electricity is eventually consumed.

The reason these impacts remain widely invisible is not that they are small or rare, but that the tools used to evaluate renewable energy environmental performance were not designed to capture them. Carbon emissions during electricity generation are near zero for wind and solar and this is genuinely positive. However, this metric only measures performance at the end of the supply chain, not at the beginning, and it says nothing about what happens in the mines, refineries, and processing facilities that make this generation possible. As deployment grows and each additional gigawatt requires more minerals than before, the environmental footprint of this upstream activity grows accordingly and still remains absent from the assessments that give renewable energy its green credentials.

This is where the comparison with fossil fuels becomes particularly revealing. Upstream environmental damage in fossil fuel supply chains such as oil spills, gas flaring, coal mine degradation, has been documented and at least partially regulated over decades, precisely because the fossil fuel industry was never given the benefit of the doubt on environmental questions and since renewable energy has always been seen as the clean alternative to fossil fuels and carried a green identity, the environmental damage that happens during the extraction of its materials receives far less attention than it deserves and the same damage that would be questioned and regulated if it were associated with oil or coal , goes unnoticed when it is associated with solar panels and wind turbines.

3.1.4 Social and Labor Conditions in Mining Regions:

The social dimension of the upstream stage is the hardest to measure. Of the 94 data points collected in this research database, only 5 relate to social indicators, representing 5% of the total which mirrors and confirms what Hmouda et al. (2024) found in their review that the social dimension is the most neglected pillar in sustainable energy supply chain research. The low number of social data points does not mean that social issues are absent, it means they are not being measured and reported, which is itself a serious problem.

The social data that is available, although limited, points to real concerns. In Ecuador, which supplies 90% of the balsa wood used in wind turbine blades globally, the increase in demand from the wind energy sector has led to cutting on lands that legally belong to local communities raising questions about the rights of the people living closest to the extraction activities that the energy transition depends upon.

Additionally to this specific case, there is a wider problem that affects the entire upstream stage is when minerals leave the mine and pass through multiple processing steps before becoming part of a solar panel or a wind turbine, it becomes increasingly hard to know where they came from, who extracted them, and in what conditions, and by the time the finished component reaches the manufacturer, this information has largely been lost along the way, creating what supply chain experts call a traceability problem, a challenge that has been officially acknowledged in the wind energy sector (EBRD, 2024) which means that even when there are reasons to believe that workers were not treated fairly or that the environment was damaged, there is no way to confirm this, no way to address it, and no one who can be held responsible for it and a supply chain where traceability is absent cannot honestly claim to meet social sustainability standards, no matter how green the final product appears.

3.1.5 Triple Bottom Line Assessment of the Upstream Stage:

The analysis of the upstream stage across the three dimensions of the Triple Bottom Line produces a clear and consistent result, which is that the upstream stage does not meet sustainability criteria on any of the three dimensions, and what makes this finding important is that the three failures are not independent of each other but are deeply connected, with each one reinforcing the others in a way that makes the upstream stage difficult to improve without addressing all three the same time.

The concentration of critical mineral supply in a small number of countries, averaging 83.8% across the five upstream mineral indicators reviewed in this research, is not only an economic problem but is also the main reason why environmental damage at the extraction stage is so hard to regulate and why social conditions in mining regions are so hard to monitor, because when most of the critical minerals are controlled by a small number of countries, the companies that buy these materials have very little power to impose environmental or social standards on their suppliers, and the same concentration that creates economic weakness also creates the conditions under which environmental and social problems can continue without being addressed or noticed.

This matters for sustainability assessment because improving one dimension in isolation cannot solve the others, and reducing carbon emissions during electricity generation does nothing to address the land damage, the community concerns, or the supply risks that exist at the extraction stage, meaning that the upstream findings do not simply show that renewable energy supply chains perform poorly on sustainability but that the way sustainability is currently measured underestimates the stage where the most serious problems actually occur.

Based on the TBL scoring framework applied in this research, where 0 means the stage fails, 1 means it partially meets the criteria, and 2 means it fully meets them, the upstream stage scores 0 on all three dimensions, giving a total of 0 out of 6 representing the lowest score of any stage in the supply chain, and a result that sits in sharp contrast to the sustainability image that renewable energy most commonly projects.

Table 2:Upstream Stage—Triple Bottom Line Result

Dimension	Score (0–2)	Verdict
Environmental	0	**Fails**
Economic	0	**Fails**
Social	0	**Fails**
Total	**0 / 6**	**Fails**

3.2 *Midstream Supply Chain Analysis*:

3.2.1 Manufacturing Concentration and Supply Chain Dependency:

If the upstream stage revealed a supply chain concentrated in a small number of countries for the extraction of raw materials, the midstream stage shows that this concentration does not reduce as materials move further along the chain but actually deepens, and when the manufacturing data compiled in this research is examined as a whole, the average market share controlled by China across the five midstream manufacturing indicators reaches 77.4%, a number that does not appear in any single institutional source but comes from combining and averaging the individual concentration data collected across the sources used in this study.

For solar PV, China controls 97% of global wafer production, 80% of polysilicon processing, 80% of solar cell production, and 70% of solar module assembly, which means that every step of the solar PV manufacturing process from the first treatment of raw silicon to the final assembly of a panel ready for installation, is dominated by a single country, and any disruption at any one of these steps has the potential to affect solar PV production across the entire world. For wind energy, the situation is no different, with China controlling 82% of power converter production, 80% of gearbox manufacturing, 76% of offshore wind foundation production, 73% of generator manufacturing, 61% of blade production, and 60% of both turbine and nacelle manufacturing leaving the rest of the world almost entirely dependent on Chinese factories for the components needed to build wind turbines.

What makes this concentration different from what was found at the upstream stage is its origin. At the upstream stage, concentration existed because certain minerals are only found in certain parts of the world, which is a natural reality that is very difficult to change, but at the midstream stage the situation is different because China did not come to dominate renewable energy manufacturing by accident, it built this position over decades by investing heavily in factories, workforce, technology and through government support, while Europe and North America moved their own production elsewhere to reduce costs, and the result today is that Europe produces only 21.6 GW per year of wind nacelle assembly capacity against a global total of 163 GW, manufactures only 700 offshore wind towers per year against a need that will exceed 1,100 per year from 2028, and finds itself unable to produce the components needed to meet its own renewable energy targets, a situation that was created by choices that were made, which means it is also a situation that could be changed, though not quickly or easily.

Fossil fuel power generation equipment has historically been manufactured across many different regions such as Europe, North America, Asia which made those supply chains more balanced and less dependent on any single country. The energy transition was expected to move in the same direction, but the manufacturing data tells a different story: rather than spreading production more widely, the transition has concentrated it further, leaving the world more dependent on a single supplier for the components that clean energy needs than it ever was for the equipment that fossil fuels required.

3.2.2 The Carbon Paradox in Manufacturing:

There is a contradiction sitting at the heart of the renewable energy transition that rarely gets discussed: the solar panels and wind turbines being built to replace fossil fuels are themselves manufactured using fossil fuel energy. This is not a minor detail or just a coincidence, it is the reality of how renewable energy components are produced today, and it is a direct consequence of the manufacturing concentration identified in the previous section.

China's electricity system runs on coal for approximately 62% of its generation, and given that China produces between 60% and 97% of every major renewable energy component, this means that the vast majority of the world's clean energy equipment is made in factories powered by one of the most carbon-intensive energy sources on the planet. A solar panel manufactured in China produces approximately 41% more CO_2 during its production than one would if made in the European Union, and 28% more than one made in Germany, where coal plays a much smaller role in powering factories. This means that the decision to concentrate manufacturing in China which the previous section showed was made to reduce costs, also had a carbon cost that nobody calculated when making that choice, and that nobody accounts for today when calling the final product sustainable.

Polysilicon production alone accounts for around 40% of the total energy consumed across the entire PV manufacturing chain, concentrating the most carbon-intensive step of the process in a country where that energy comes mainly from coal. Manufacturing solar panels in Europe would cost 15% more, with energy costs twice as high and and Europe has invested barely a tenth of what China has spent on PV manufacturing since 2011 which is why the industry chose to stay where it was, even though the environmental cost of that decision is never taken into account when using the word sustainable.

What makes this significant is that renewable energy systems carry the opposite carbon profile to fossil fuel plants. A fossil fuel plant emits carbon every day it operates, which is why operational emissions are the natural focus of environmental assessment but a renewable energy system produces no emissions once it is running, which means all the carbon it will ever be responsible for was already released during its manufacturing and if those factories ran on coal, then every panel and every turbine installed today carries a carbon footprint from its production that the green label it receives does not take into consideration.

3.2.3 Economic Fragility and Financial Risk:

The concentration of manufacturing in China that the previous section identified does not only create supply chain risks, it has also put the companies that make renewable energy components under serious financial pressure, and this pressure is one of the least discussed aspects of the sector's sustainability.

One in three solar PV manufacturers is currently at risk of going out of business, and the reason is that solar module prices have fallen by more than 25% since early 2023, which sounds positive for the energy transition but is actually very damaging for the manufacturers themselves, because when the price of what you sell drops faster than what it costs you to make it, you lose money, and for companies outside China this is hard since producing solar panels in Europe already costs 15% more, with energy costs twice as high and the investment needed to set up facilities three times higher than in China, leaving many manufacturers in a situation where they earn less from each panel they sell but cannot reduce their costs fast enough to compensate.

On top of this, borrowing money has become significantly more expensive since the pandemic, with financing costs in the energy sector rising by more than 30%, and this matters a great deal for renewable energy manufacturers because unlike oil or gas companies that earn money every single day by selling fuel to the same customers over decades, a company that makes wind turbines or solar panels earns money once when it sells its product and then nothing more from that customer which means that when interest rates go up, investing in new manufacturing capacity becomes much harder to justify financially, at exactly the moment when the supply chain needs to grow the most.

The numbers behind the investment gap make this concrete. Global clean energy investment reached 1.4 trillion USD in 2022, but meeting the demands of the energy transition by 2035 will require around 5 trillion USD per year representing more than three times what is currently being invested and the EU alone faces a solar manufacturing financing gap of 30 billion EUR, which shows that the economic sustainability of the midstream stage cannot be evaluated simply by looking at how affordable clean electricity has become, because the companies responsible for producing it are struggling financially in ways that the falling price of a solar panel does not reveal.

3.2.4 Manufacturing Capacity Gaps and the 2030 Targets:

The financial fragility mentioned earlier, it directly affects the ability of the renewable energy sector to build the manufacturing capacity needed to meet the targets the energy transition has set for itself, and when the current production numbers are placed alongside what the 2030 targets actually require, the gap between the two is difficult to ignore with the optimistic narratives that surround the energy transition.

At the end of 2024, total global renewable energy capacity stood at 4,443 GW, while the target set for 2030 is 11,000 GW meaning that the sector needs to more than double its installed capacity in less than six years, which means the sector needs to add at least 1,000 GW every single year starting from 2025. In 2024, solar PV installations reached 452 GW and wind reached 114 GW given a combined total of 566 GW, which is barely half of what is needed annually. The problem is not that the world does not want more clean energy but the factories and supply chains needed to produce it at this speed are not yet in place.

Looking at wind energy specifically makes the problem even more visible. To meet the 1.5°C pathway, cumulative wind capacity needs to reach 2,750 GW by 2030, but current forecasts only project 2,100 GW leaving a gap of 650 GW that represents not a technical failure but a manufacturing and investment one, because the turbines, blades, nacelles, and foundations needed to close this gap cannot be produced fast enough by a supply chain that is financially fragile, geographically concentrated, and operating at only 40% of what they could actually produce.

What these numbers reveal is that the renewable energy sector faces a fundamental tension between the speed at which it needs to grow and the conditions under which its supply chain is currently operating and this tension has a direct economic dimension, because global clean energy investment reached 1.4 trillion USD in 2022 which sounds substantial until you realize that meeting the demands of the energy transition by 2035 will require around 5 trillion USD every year, meaning the world is currently investing less than a third of what is actually needed, and the EU alone faces a solar manufacturing financing gap of 30 billion EUR, which shows just how far the money available today falls short of what the transition requires.

3.2.5 Social Conditions in manufacturing:

While the upstream stage revealed a near total absence of social data, the midstream stage contains the most serious social concern in the entire renewable energy supply chain concentrated in a single location that accounts for 42% of global solar PV manufacturing: Xinjiang, a region in northwestern China where the United Nations has officially documented serious human rights violations, and where under United States legislation, any product made there is legally presumed to involve forced labor unless the manufacturer can prove otherwise.

The same source that documents Xinjiang's share of global PV manufacturing also confirms that 42% of global PV manufacturing is at forced labor risk and both numbers pointing to the same place, which means that nearly half of the world's solar panels are made in a region where working conditions cannot be checked by anyone outside of it, and where what is known about the situation raises serious human rights concerns that are never mentioned when the final product is called sustainable.

A supply chain that sources nearly half of its most important manufacturing from a region associated with forced labor cannot be called socially sustainable, and the fact that this is rarely discussed in public conversations about renewable energy is itself a reflection of what section 1.5 of this research identified that the green image of the sector makes certain problems much easier to overlook.

3.2.6 Triple Bottom Line Assessment of the Midstream Stage:

The midstream stage presents a more mixed picture than the upstream stage, but the overall assessment remains deeply problematic when examined across all three TBL dimensions at the same time.

On the environmental dimension, the midstream stage receives a partial score of 1 out of 2. The carbon paradox documented in section 3.2.2 shows that renewable energy components are manufactured using coal-powered electricity, meaning that the manufacturing process carries a real carbon footprint that is never counted in official sustainability assessments. However, it is worth acknowledging that PV emissions intensity has fallen by 40% between 2010 and 2022, showing that the sector is moving in the right direction even if it has not yet resolved the fundamental contradiction of building clean energy using dirty energy.

On the economic dimension, the midstream stage scores 0 out of 2. The combination of extreme manufacturing concentration at 77.4%, financial fragility affecting one in three manufacturers, a 25% collapse in module prices, a 30% increase in financing costs, and an investment gap of more than three times what is currently being used makes it impossible to consider the midstream stage economically sustainable when assessed across the whole chain.

On the social dimension, the midstream stage receives a partial score of 1 out of 2. The Xinjiang situation is serious and this alone makes it impossible to give this dimension a full score. However, since not all renewable energy manufacturing happens under these conditions, a score of 0 would not be accurate either. The reality sits somewhere in between, which is what a score of 1 reflects

Based on this assessment, the midstream stage scores 1 on environmental, 0 on economic, and 1 on social, giving a total of 2 out of 6 representing a result that reflects a stage where some progress is visible but where the economic and social failures are serious enough to prevent any honest claim of full sustainability.

Table 3: Midstream Stage—Triple Bottom Line Result

Dimension	Score (0–2)	Verdict
Environmental	1	**Partial**
Economic	0	**Fails**
Social	1	**Partial**
Total	**2 / 6**	**Partial**

3.3 Operation stage Analysis:

Economic Performance:

The operation stage is where renewable energy performs best, and the numbers in this research make this clear. In 2024, global renewable energy capacity additions reached 582 GW, with solar PV accounting for 77.8% of all new additions and wind for 19.6%, these numbers that reflect not just a political choice but a real economic shift. By this, renewable energy has simply become the cheapest way to produce new electricity in most parts of the world.

The cost data tells this story directly. Onshore wind now costs 0.034 USD per kilowatt-hour globally and solar PV costs 0.043 USD per kilowatt-hour, compared to 0.073 USD for coal and 0.085 USD for gas, meaning that onshore wind is 53% cheaper than fossil fuels and solar PV is 41% cheaper, and in 2024, 91% of all new renewable energy capacity added worldwide was cheaper than the cheapest fossil fuel alternative available in the same market. Battery storage used to store the electricity produced by solar and wind so it can be used when the sun is not shining or the wind is not blowing, costs have fallen by 93% since 2010, and in 2024 alone, renewable energy saved the world approximately 467 billion USD to be spent in fossil fuel costs which shows that the financial benefits of the energy transition are no longer just a promise, they are already happening.

The regional cost picture adds an important nuance. China's onshore wind costs 0.029 USD per kilowatt-hour compared to 0.051 USD in the United States, and Chinese offshore wind costs 0.056 USD compared to 0.123 USD in the United States, a gap that reflects the same manufacturing concentration documented in section 3.2, where China's dominance of the supply chain translates directly into lower production costs, meaning that countries most dependent on Chinese components pay more for the same equipment than China does since it is not charged by the import taxes neither profit margins that other countries face when buying, creating a cost gap that the global energy transition has not yet resolved.

3.3.1 Environmental Performance:

The operation stage is where the environmental case for renewable energy is at its strongest. Wind turbines and solar panels produce no direct carbon emissions when they are running, they generate electricity without burning anything and without releasing greenhouse gases, which is the core environmental argument that has driven the global shift toward clean energy.

The contrast with fossil fuels makes this concrete. According to the IPCC Fifth Assessment Report (2014), Coal power produces 820 grams of CO2 for every kilowatt-hour of electricity it generates, while wind and solar produce none during operation and this difference is not small, it is the entire reason the energy transition exists.

It is important to note however that this does not erase what was found in the previous sections. The carbon released during manufacturing still happened, the mining damage still occurred, and the social problems at the upstream and midstream stages do not disappear simply because the panels and turbines are now running cleanly. The operation stage delivers on its environmental promise but it is only one part of a much longer chain.

3.3.2 Triple Bottom Line Assessment of the Operation Stage:

The operation stage is the strongest performing stage in the renewable energy supply chain, and the TBL assessment reflects this clearly.

On the environmental dimension, the operation stage scores 2 out of 2. Wind and solar produce no direct carbon emissions during operation, fully meeting the environmental sustainability criteria at this stage.

On the economic dimension, the operation stage scores 2 out of 2. Renewable energy is now cheaper than fossil fuels in most markets, with 91% of new capacity added in 2024 cheaper than the cheapest fossil fuel alternative, fully meeting the economic sustainability criteria at this stage.

On the social dimension, the operation stage scores 1 out of 2. Renewable energy supports 16.2 million jobs globally as of 2024, which is a genuine social contribution. However, China accounts for 61.2% of global solar additions and 69.4% of global wind additions, meaning that the majority of the social and economic benefits generated at this stage are concentrated in one country rather than distributed globally which makes a full score impossible to justify.

Based on this assessment, the operation stage scores 2 on environmental, 2 on economic, and 1 on social, giving a total of 5 out of 6 representing the highest score of any stage in the supply chain, and the one stage where the sustainability label applied to renewable energy is most honestly deserved.

Table 4: Operation Stage—Triple Bottom Line Result

Dimension	Score (0–2)	Verdict
Environmental	2	**Passes**
Economic	2	**Passes**
Social	1	**Partial**
Total	**5 / 6**	**Passes**

3.4 End of life stage analysis:

The end-of-life stage is the most forgotten part of the renewable energy supply chain, and yet it is one of the most important ones to examine because the first solar panels installed at scale in the early 2000s are now reaching the end of their operational life, and the infrastructure needed to handle what comes next is largely not ready.

The data built for this chapter contains only one end of life data point and that single number says a lot. It tells us that rare earth recycling from old wind turbines and solar panels will only become possible at large scale from 2026 onwards, meaning that today, the tools needed to recover and reuse the critical materials embedded in these systems simply do not exist yet. Having only one data point for an entire supply chain stage is not a coincidence but it reflects the fact that the renewable energy sector has spent the last two decades focused on building and installing systems, while giving almost no attention to what happens when those systems eventually stop working.

Sharma et al. (2024) shows how serious this problem already is. Solar panels contain toxic materials including lead and cadmium which, if thrown into landfill, leak into groundwater and cause serious damage to human health and the environment and yet only 10% of global solar PV waste is currently being recycled, meaning 90% is being disposed of in ways that carry real environmental risks. The same study shows that recycling panels properly could reduce their environmental impact by up to 70%, and that the materials recovered such as aluminum, glass, copper, and silicon could be reused in new manufacturing, but this is not happening at scale because most countries outside the European Union have no specific rules governing what to do with solar waste at the end of its life.

Wind turbine blades add another layer to this problem. Made from materials that cannot currently be recycled, most old blades end up in landfill and as the large turbines installed during the 2010s start reaching the end of their lives over the next decade, this problem will grow considerably.

What this stage reveals more than any other is that renewable energy was built to be deployed, not to be circular and the sustainability label it carries has never seriously accounted for what happens at the end.

3.4.1 Triple Bottom Line Assessment of the End-of-Life Stage:

The end-of-life stage scores 0 out of 6 making it the joint lowest performing stage in the supply chain. All three dimensions fail: the environmental infrastructure to handle toxic waste does not exist at scale, no functioning circular economy has been built for renewable energy components, and social governance of end-of-life disposal is almost entirely absent. The result is a stage that has been disregarded in sustainability assessments of renewable energy, despite the fact that it is now beginning to arrive.

Table 5: End-of-Life Stage—Triple Bottom Line Result

Dimension	Score (0–2)	Verdict
Environmental	0	**Fails**
Economic	0	**Fails**
Social	0	**Fails**
Total	**0 / 6**	**Fails**

3.5 Overall Triple Bottom Line Verdict:

The TBL scoring framework applied across the four stages of the renewable energy supply chain produces an overall score of 1.75 out of 6, corresponding to a verdict of fails. When represented by stage it showed as following: upstream scores 0 out of 6, midstream scores 2 out of 6, operation scores 5 out of 6, and end of life scores 0 out of 6.

The operation stage is the only stage that performs well, confirming that renewable energy delivers on its core promise of clean and affordable electricity generation. However, this stage represents only one part of the supply chain, and its strong performance cannot compensate for the failures identified at the three remaining stages where environmental damage, economic fragility, social invisibility, and the near-total absence of end-of-life infrastructure produce scores that fall far short of what the TBL framework requires.

Three out of four stages fail or only partially meet sustainability criteria, and the overall score of 1.75 out of 6 reflects a supply chain that performs well where it is most visible and most measured, while failing where it is least examined. Taken together, these findings suggest that the answer to the central research question of this study, *are renewable energy supply chains sustainable when all three dimensions are considered across the full lifecycle?* is no, not in the complete sense that the Brundtland definition and the Triple Bottom Line framework require.

Chapter 4 : Case Study: NOOR Ouarzazate, Morocco:

4.1 Project Overview:

The NOOR Ouarzazate Solar Power Station is one of the largest solar energy projects in the world, located in southern Morocco near the city of Ouarzazate. Built in four phases between 2012 and 2016, it combines concentrated solar power and photovoltaic technologies to reach a total planned capacity of 500 MW, making it the centerpiece of Morocco's national energy transition strategy.

The project was financed by several international institutions: the World Bank, the European Investment Bank, the African Development Bank, The German Development bank KFW, and French Development Agency AFD, with a total investment of approximately 28 billion Moroccan dirhams, equivalent to between 2.5 and 2.8 billion US dollars.

Because so many international institutions were involved, each one produced its own independent evaluation of the project including the World Bank Implementation Completion and Results Report published in March 2025 which makes NOOR one of the rare cases where it is actually possible to check whether the sustainability promises made at the beginning were kept by the end.

This is why NOOR was chosen for this research, it was officially presented as sustainable, it is well documented, and which makes it a good case to test whether the sustainability label applied to it was backed by evidence or not.

4.2 Triangulation approach and Methodology:

The approach followed in this chapter is different from the one applied in Chapter 3. Rather than analyzing a database of quantitative indicators, this chapter compares what the official project documents claimed about NOOR's sustainability against what independent sources actually found, a process known as triangulation.

The official documents used are the Environmental and Social Impact Assessments produced by MASEN for each of the four phases of the project which are FESIA (2014) for the complex as a whole, and the individual Non-Technical Summaries for Noor I (2012), Noor II (2015), Noor III, and Noor IV (2016). These documents represent what the developer promised about the project's environmental, economic, and social performance before construction began. They are classified in the NOOR database as ESIA claims.

These claims are then compared against three independent sources: the World Bank Implementation Completion and Results Report (WB-ICR, 2025), the academic study by Laaroussi (2023) on the environmental impacts of the Noor I project, and an expert interview conducted with a former senior official of NOMAC, the company responsible for operating the NOOR complex. Each testable claim drawn from the ESIA documents is classified as confirmed, contradicted, partially supported, or omitted meaning it was never addressed in the ESIA at all.

The NOOR database constructed for this research contains 65 data points, covering the environmental, economic, and social dimensions across all supply chain stages. Additional tests are applied: the first examines whether the ESIA covers all three TBL dimensions equally, the second checks whether the full supply chain lifecycle is included in the assessment, and the third identifies which supply chain elements were excluded from the assessment boundary entirely.

4.3 Environmental Dimension:

The NOOR project was officially presented as an environmentally responsible project, and the main argument used to support this claim was that it would produce clean electricity while avoiding important quantities of CO_2 that would otherwise be released by fossil fuel-based plants. When three different sources are examined alongside the official project documents, what emerges is not simply a story of missed targets but a pattern where the environmental assessment chose to measure what supported the green image of the project while leaving out what did not.

The CO_2 promise is the clearest example. The ESIA for Noor I and Noor II each claimed the project would avoid more than one million tons of CO_2 per year. On the other hand, The World Bank found that the whole complex avoided 807,789 tons per year in reality. The reason this gap exists is that the ESIA assumed the plant would always produce electricity at its maximum possible output, but in practice it never did, and an assumption that was too optimistic from the start produced a CO_2 number that was never going to be achieved.

Water consumption reveals the same pattern but in a more serious way. The ESIA reported that Noor I would use 1.75 million cubic meters of water per year during operation, presenting this as a small and manageable share of the total reservoir capacity. Laaroussi (2023) found that actual consumption reached 6 million cubic meters per year, which is more than three times what the official documents had claimed, and what makes this gap significant is not just its size but the questions that the ESIA never asked whether this level of water use would compete with local farmers who depend on the same reservoir in a desertic region where water is already extremely scarce, and whether the synthetic oil used in the plant could contaminate nearby water sources if it leaked. These were not impossible questions to ask at the time the assessment was written, but they were outside the boundary that the developer chose to draw, and that boundary was drawn in a way that made the environmental picture look cleaner than it actually was. The expert interviewed for this research confirmed this from direct experience, the former Head of Electrical Department at NOMAC acknowledged that in renewable energy projects, attention in practice goes to performance, reliability, and cost, while environmental impacts that are harder to see tend to remain in the background.

On biodiversity, the ESIA concluded that the impact on local vegetation and wildlife would be low despite the presence of five protected areas within fifteen kilometers of the site, and Laaroussi (2023) found real losses of native vegetation and wildlife habitat that the official assessment had not anticipated. The World Bank completion report also documents that the molten salt storage tanks at Noor III developed serious leaks caused by extreme heat and construction problems, leaving the plant unable to produce electricity for an extended period while repairs were carried out representing a risk that the ESIA had never mentioned.

What connects all these findings is one consistent pattern: the environmental assessment looked carefully at what the project produces while paying much less attention to what it consumes, damages, and puts at risk.

4.4 Economic Dimension:

The NOOR project documents made three main economic promises: the plant would generate significant electricity, create jobs, and deliver economic benefits for Morocco. The World Bank completion report, which officially rated the project outcome as Moderately Unsatisfactory, shows that none of these three promises was fully kept and the economic findings raise deeper questions about whether the project was ever genuinely economically sustainable.

Since electricity generation was the basic promise and the main goal of the project, Noor II and Noor III together were expected to produce 1,144 GWh per year, but the actual average between 2019 and 2023 was 739 GWh, which is 35% below what was planned, and this gap in production translated directly into a gap in revenue since the project achieved only 1,500 GWh in electricity sales against a target of 2,624 GWh, reaching barely 57% of what had been promised to the institutions that financed it.

Behind these missed targets is a more fundamental economic problem that the official documents never addressed. Before construction even began, the World Bank calculated that NOOR would cost more than it would earn from selling electricity alone, giving the project a negative Economic Rate of Return of minus 0.07% and the only way to bring this number above zero was to assign a financial value to the CO2 emissions that the plant avoids compared to a fossil fuel-based plant, treating each ton of avoided carbon as worth 40 US dollars and even with this assumption, the return reached only 0.89%, which the World Bank itself described as barely positive. In simple terms, NOOR is only financially viable on paper if its environmental benefit is counted as money without that, it costs more than it earns and a project that cannot generate a positive economic return without that carbon value assumption cannot honestly be called economically sustainable.

The question of where the economic value actually went makes this picture more troubling. Only 30% of the total investment stayed in Morocco, mainly invested in basic construction works and local materials, while the other 70% went abroad (World Bank, 2025, p. 11). This is not surprising when you consider what the project required: generators, turbines, pumps, and transformers, all technologies that Morocco does not manufacture and that had to be imported from Spain, China, and Germany, as the former Head of Electrical Department at NOMAC confirmed already in the interview. A project presented as a driver of Moroccan economic development sent most of its budget abroad not by accident, but because the supply chain concentration documented in Chapter 3 left no alternative and the project could not escape this dependency by calling itself sustainable.

4.5 Social Dimension:

The social dimension is one of the most levels where the gap between what was promised and what actually happened is visible and noticed because the people most affected by NOOR were not international financiers or policymakers, but local communities in the Ouarzazate region who gave up their land, expected jobs, and were promised a better quality of life.

For the land side, the project required 2,500 hectares from the Ait Ougrour collective, tribal land that had belonged to a local community for generations transferred to MASEN through the Ministry of Interior at 10,000 Moroccan dirhams per hectare, totalling 25 million dirhams.

Whether this price was fair, and whether the community had a real choice in the matter, are questions the ESIA never asked and that no other source has been able to answer. For a project that claimed social sustainability as one of its pillars, the silence on this point is significant.

The project promised job creation as well. During construction, 8,504 workers were employed against an ESIA estimate of 2,250, with 6,077 Moroccan and 2,383 from the local Ouarzazate region and these numbers look impressive until you realize that construction jobs end when building stops. By 2022, only 234 permanent operation jobs remained for the entire complex against a promise of 450, and only 26 of these were held by women. The project created temporary employment and very little permanent employment which is a distinction the official documents never clarify when presenting the social level for NOOR.

On energy access, 1,298,960 people received new or improved electricity service against a target of 2,200,000 that represent 59% of what was promised. A further 23,526 people benefited from local development initiatives in irrigation, drinking water, health, and education. These are real contributions, but they are considerably below what was committed to the institutions that financed the project.

4.6 Supply chain coverage of the ESIA:

The three previous sections examined what NOOR promised and what it delivered across the environmental, economic, and social dimensions. This section asks a different question: what did the assessment choose not to look at, and what does that exclusion reveal about how sustainability was defined for this project?

The ESIA documents for NOOR assessed the project almost entirely at the point of electricity generation, the operation phase of the plant itself. What they did not examine is everything that happened before the plant started running and everything that will happen after it stops. On the upstream side, the evaluation contains no information of where the mirrors, steel structures, solar panels, molten salts, heat transfer fluid, or rare earth magnets came from, how they were manufactured, under what conditions, or what environmental and social impacts their production created in the countries of origin. On the end-of-life side, no assessment was made of what will happen to these components when the plant stops working permanently and how the toxic materials will be managed, who will pay to take everything apart, and whether any of the critical materials can be recovered and reused.

This exclusion is not a technical neglect, it is a boundary choice and it is the same boundary choice that the literature review identified as the defining characteristic of how sustainability is communicated in the renewable energy sector: evaluate the part that looks best, and define the boundary so that the parts that look worst fall outside the circle. At NOOR, the boundary was built around the operation phase because that is where the CO2 avoided is generated and where the project's green credentials are strongest. The upstream supply chain where components were sourced from China, Spain, and Germany through a highly concentrated international supply chain and the end-of-life stage where no recycling infrastructure exists, were simply left out.

The expert interviewed for this research confirms this from direct experience. When asked whether renewable energy projects take into account the environmental impacts of manufacturing and supply chain, the former Head of Electrical Department at NOMAC acknowledged that in practice, attention focuses on performance, reliability, and cost, while the environmental and social impacts linked to equipment manufacturing are less noticed at the operational phase. This is precisely what the scope of the NOOR assessments reflects, a project evaluated as sustainable within a boundary that was designed to make it look sustainable.

The triangulation matrix constructed for this research tested 14 sustainability claims from the NOOR ESIA documents against independent sources. Of these 14 claims, only 1 was independently confirmed, 7 were contradicted, 4 were omitted entirely from the official assessment, and 2 were only partially supported. This result does not mean NOOR is a failed project, it means the sustainability label applied to it was built on an assessment that was too narrow, too optimistic, and too focused on the generation phase to honestly represent the full sustainability performance of the project across its supply chain and lifecycle.

4.7 Overall assessment:

The NOOR case study confirms at the project level what the global supply chain analysis found at the sector level: renewable energy performs well where it is most visible and most measured, while the stages that precede and follow electricity generation remain largely unexamined and underperforming.

NOOR is not a failed project, it produces real clean electricity, created jobs, and contributed to Morocco's energy transition, but the fact that even a project this well-funded and this well documented, and monitored by multiple international institutions, still excluded the upstream supply chain, still ignored the end-of-life stage, and still produced promises that independent sources found to be consistently overstated across all three TBL dimensions.

The expert interviewed for this research closes this picture from the inside. When asked about the main challenges for making renewable energy supply chains more sustainable, the former Head of Electrical Department at NOMAC identified four: where materials come from, reducing manufacturing and transport emissions, managing end of life waste, and ensuring that international suppliers respect social and environmental standards. These four challenges correspond directly to the four supply chain stages examined in Chapter 3 of this research. And when asked directly whether renewable energy supply chains can today be considered truly sustainable, his answer was clear: no, not yet. Manufacturing and transport still have real impacts, traceability and recycling remain unsolved, and full sustainability is still a goal rather than a reality. This answer, from someone who worked for years inside one of the world's largest solar projects, is a direct confirmation of the argument this research makes.

Chapter 5 : Survey Results and Perception Analysis:

5.1 Survey Design and Sample Characteristics:

The perception survey designed for this research contains 11 questions and it follows a before and after structure: respondents are first asked to rate the sustainability of renewable energy and indicate what they associate with the concept, before being presented with three factual statements about the upstream and end of life stages of the supply chain that are rarely discussed in public debate. After reading these facts, they are asked to rate renewable energy sustainability again and the gap between the two ratings is the core quantitative finding of the survey.

The minimum sample size was estimated using the Yamane formula, which indicated a minimum of 100 responses. The survey collected 115 responses, exceeding this benchmark, distributed across student networks at HEC Liège, ENCG Agadir and Marrakech, the Ferrero ecosystem where the researcher is completing an internship, as well as through LinkedIn.

In terms of sample composition, 102 respondents identified as students (88.7%), with the remaining 13 coming from professional backgrounds including supply chain and logistics, energy sector, management, and academia. On age, 94 respondents were under 25 (81.7%), 18 were between 25 and 35 (15.7%), and 1 was between 36 and 50. The sample is mainly young and more student-oriented, which reflects the distribution channels used. However, if even young educated respondents who are generally more environmentally aware show a significant perception gap when exposed to supply chain reality, and if this is true for the most informed and the most digitally connected segment of the population, it is likely to be even larger than what this survey found.

Table 6:Sample Size Determination—Yamane (1967)

Formula	$n = N / (1 + N \times e^2)$
Where	
n	Required sample size
N	Target population
e	Margin of error
Parameters	
Target population (N)	General public
Confidence level	90% (e = 0.10)
Required sample size	100
Achieved sample size	115

5.2 Initial understanding of sustainability:

When asked what comes to mind first when thinking of renewable energy as sustainable, more than half of respondents which is 64 out of 114, representing 56.1%, said clean electricity with no emissions. Only 36 respondents (31.6%) thought of responsibly sourced materials, 11 (9.6%) of economic stability, and 3 (2.6%) said they had never thought about it.

This means that before seeing any supply chain information, most people's understanding of RE sustainability stops at the generation phase where the electricity is produced. The mining, the manufacturing, the end of life, none of these come to mind spontaneously for the majority of respondents. This is exactly the perception gap this research set out to measure, and it appears before the survey even asks people to think critically. One respondent expressed this framing in their own words: *"First, I can't consider it unsustainable until I see the damage caused by the non-sustainable, to have a fair comparison".* This response captures precisely the perceptual mechanism the statistics describe, sustainability evaluated through what is visible at the point of generation, with the rest of the supply chain remaining outside the frame of judgment until the damage is shown.

What makes this finding analytically important is that it was not produced by ignorance. The respondents who associated RE sustainability with clean electricity are not wrong, clean electricity is a genuine benefit of renewable energy, as the literature review and the operation stage analysis both confirm. But associating sustainability exclusively with this one benefit, while remaining unaware of what happens across the rest of the supply chain, is precisely the incomplete understanding that this research has been arguing exists and the survey confirms it is real.

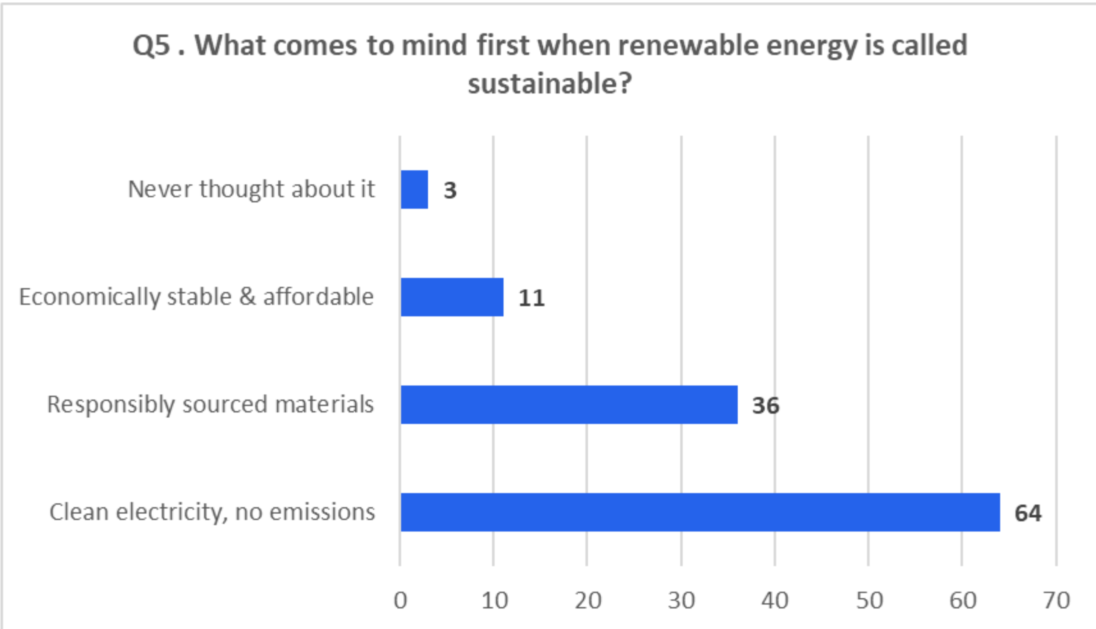

Figure 1:First association with «sustainable» in renewable energy

5.3 The Perception Gap Before and After Exposure:

This section tests the following hypotheses:

- **H0:** there is no difference between pre-exposure (Q4) and post-exposure (Q8) perceptions of renewable energy sustainability.
- **H1:** a statistically significant difference exists between Q4 and Q8.

Of the 115 responses collected, 114 provided valid answers to both questions and were included in the paired analysis, and before being shown any supply chain information respondents gave renewable energy an average sustainability rating of 3.228 out of 5, which after reading three facts about upstream mining conditions, manufacturing carbon emissions, and the absence of end of life recycling infrastructure dropped to 2.807 which is a decrease of 0.421 points confirmed by a paired samples t-test producing *t(113) = 4.26* with *p < .001* and *Cohen's d = 0.399*, and a *Wilcoxon signed-rank* test producing *z = 3.85 with p < .001* and r = 0.526 (Appendix G.1,G.2) , with both parametric and non-parametric tests agreeing that the null hypothesis is rejected and that the difference between Q4 and Q8 ratings is statistically significant.

The transition at the individual level confirms this, because before exposure 48 respondents gave a rating of 3, 40 gave a 4, and nobody gave a 1, while after exposure the number of respondents giving a 1 went from 0 to 7, those giving a 2 went from 22 to 34, and those giving a 4 dropped from 40 to 18, the same 114 people, rating the same concept, after seeing three facts about the supply chain they had not previously considered, and not a single respondent gave a higher rating after exposure than before.
This finding supports the central argument of this research, because the sustainability label applied to renewable energy is built around the parts of the supply chain that perform best while the parts that perform worst remain largely unknown to the public, and when those parts are made visible even briefly through three factual statements, the perception changes in a measurable and statistically confirmed way.

5.4 The Role of Awareness and Behavior:

Using a Spearman rank-order correlation, this section tests the following hypotheses:

- **H0:** there is no monotonic association between how much respondents inform themselves about sustainability, sustainable practice, and respondents' ratings of renewable energy.
- **H1:** a statistically significant association exists between at least one pair of variables.

To understand whether the drop between Q4 and Q8 was driven by a specific type of respondent, the Spearman rank-order correlation was run on four variables: the pre-exposure rating (Q4), the post-exposure rating (Q8), how often respondents inform themselves about sustainability (Q6)[1], and how often they put sustainable practices into action in their daily life (Q7).

Of the six pairs tested, three reached significance and these results give a first picture of how engagement with sustainability relates to the perception of renewable energy. Respondents who reported acting on sustainability in their daily life give higher ratings after seeing the supply-chain facts (ρ = 0.308, p = .001), which indicates that they adjusted their view less because they already had a more realistic understanding of renewable energy, and the open responses give a face to this more measured baseline when a respondent described full sustainability as covering "the entirety of the life cycle of the energy, from womb to cradle, with all those steps including ethical, environmental and social aspects*"(respondent's words)*, an acknowledgement already aligned with the Triple Bottom Line and the full supply chain perspective adopted in this research. Respondents who inform themselves were also the ones most likely to rate renewable energy no

[1] *The variables measuring information-seeking (Q6) and sustainable practice (Q7) were both coded on a 1 to 4 scale, where 1 corresponds to "never" and 4 to "regularly", meaning that higher values indicate more frequent engagement in each behavior.*

less than their pre-exposure rating after seeing the supply-chain facts (ρ = 0.240, p = .013), showing that the people who inform themselves about sustainability are also the ones who keep a higher rating after seeing the facts, so the two go together. Before the supply-chain information was introduced, respondents who act on sustainability gave slightly higher pre-ratings than those who do not (ρ = 0.215, p = .021).

The three non-significant results are where the analytical weight of this test sits and they need to be read together with what came before. After exposure to the supply-chain facts, the association between post-exposure ratings and how often respondents act on sustainability in their daily life effectively disappears (ρ = -0.036, p = .709), and the relationship between the pre-exposure rating and the same behavioral variable is no longer significant (ρ = -0.163, p = .090). What this means: before the information was shown, informed and less-informed respondents held a roughly similar view of renewable energy, and after the information was shown that similarity broke down because the less-informed respondents lowered their ratings the most, converging toward the level of those who were already engaged with sustainability.

The null hypothesis is therefore partially rejected, and the drop observed in section 5.3 becomes easier to explain. The people who had already looked at the supply chain (the informed ones) still rated renewable energy positively, meaning the rating drop is not caused by the facts themselves being damning, but by the gap between what the public believes and what the supply chain actually involves. The informed respondents had already closed that gap before the survey began, so their rating barely moved. The less-informed respondents had to close it during the survey, and that is why their rating fell. This result supports the main argument of this research, which is that the sustainability label given to renewable energy holds in the eyes of the public not because the public has actually checked it, but because most people accept it without ever seeing the full supply chain, and when that missing part of the picture is finally shown to them, their opinion of renewable energy drops.

5.5 Perceived accuracy of the sustainability label:

After reading three factual statements about the upstream and end of life stages of the renewable energy supply chain, respondents were asked whether they considered the word sustainable to be accurately applied to renewable energy. This section tests whether their answer depended on what they had previously associated with RE sustainability. The following hypotheses are tested using Chi-Square Test of Independence:

- **H0:** Q5 and Q9 are independent.
- **H1:** They are associated

The chi-square test produced χ^2 (6, N = 113) = 5.448, p = .488, with a Cramer's V of 0.155, and H0 cannot be rejected.

But the real finding is not in the test result alone, it is in what the contingency table actually shows. After seeing the supply chain facts, 81 out of 113 respondents representing 71.7% of the sample, said the word sustainable is only partially accurate when applied to renewable energy, and the chi-square test confirms that this majority appears consistently across every group regardless of what they had previously associated with the concept whether someone had thought of clean electricity, responsibly sourced materials, economic stability, or had never thought about it at all, they all arrived at the same judgment after seeing the facts which carries an important analytical implication: the issue is not with renewable energy itself, it produces real clean electricity and that is genuinely valuable. The issue is with the word sustainable being applied to something that, when examined across its full supply chain, is not yet what the word promises and as commonly defined requires, and what this survey shows is that once people are given even a glimpse of that full picture, they see the gap themselves, across every background, every definition, every starting point. The doubt is not a minority view, it is the majority conclusion, and it is universal.

5.6 Overall Findings and Interpretation:

The three tests conducted in this chapter collectively provide empirical evidence for one of the central claims of this research: that the sustainability label applied to renewable energy reflects an incomplete picture that the public has absorbed without having access to the full supply chain reality.
The first test showed that exposure to three supply chain facts produced a statistically significant drop in how respondents rated renewable energy sustainability from a mean of 3.228 to 2.807, confirmed by both the paired t-test and the Wilcoxon test. This drop is not the result of respondents suddenly rejecting renewable energy, it is the result of respondents updating their judgment when given information they did not previously have. The fact that the drop is statistically significant tells us this is not random, it is actually a real and consistent shift in how people think once the supply chain becomes visible.

The second test showed that this shift was not uniform across respondents. Those who rarely inform themselves about sustainability started with higher ratings and dropped more, while those who already engaged with sustainability had already formed a more critical view before the survey began and this pattern confirms that the perception gap documented in this research is linked to access to information and that it narrows when people are given the supply chain facts, they were previously missing.

The third test showed that after seeing these facts, 71.7% of respondents judged the sustainability label as only partially accurate and this judgment was consistent across all groups regardless of what they had previously associated with renewable energy sustainability. The chi-square test confirmed that no single group drove this result, it is a shared conclusion that is consistent across all respondents.

Together these three findings show that the public has not fully accepted the sustainability label applied to renewable energy once they are given the chance to look beyond the generation phase and this is precisely what section 1.5 of the literature review identified as the consequence of selective sustainability communication. The survey gives this argument an empirical foundation.

Chapter 6 : Discussions

This research aims to test whether renewable energy supply chains meet the standard that the sustainability label requires, and across 94 supply chain indicators, four supply chain stages, one case study in Morocco, and 115 survey respondents, the answer is consistent : the label describes one stage accurately and is applied to four as if the difference did not matter, and understanding why this happened and what it means requires going beyond the findings themselves to ask harder questions about how sustainability is defined, measured, communicated, and ultimately trusted.

The authors reviewed in this research such as Owusu and Asumadu-Sarkodie (2016), Jelti et al. (2021), and many others, are not wrong when they call renewable energy sustainable, because at the generation phase the evidence genuinely supports them, but what Hmouda et al. (2024) found when they reviewed 97 papers is that 77 of them focus on the environmental dimension alone, which means the academic community built its judgment for RE sustainability around the stage where performance is strongest and left the rest of the chain unexamined. The result is a label that was earned at one stage and applied to four as if the conditions at one stage were representative of the chain as a whole which is precisely what Elkington (1997) warned about when he said that organizations would adopt the word “sustainability” without making the commitment needed to genuinely meet it, and what Senyapar (2024) documented when she showed that focusing only on the positive side while staying silent about less favorable one is not a feature of bad intentions but of how sustainability is communicated when reputation matters more than verification, and in the renewable energy sector, what stays silent is where the most serious challenges are concentrated.

Someone could reasonably argue that this research sets an unfair standard and that fossil fuels perform far worse on every dimension, and that pointing to RE supply chain problems without acknowledging this comparison misses the bigger picture, and this is a fair point that this research does not dispute, but fossil fuels were never labeled sustainable and that is precisely why they were regulated, taxed, and challenged, because the damage was visible and visibility created accountability, while renewable energy arrived with a different story, one where the label made looking carefully seem unnecessary and where the supply chain problems could grow quietly behind a green image that nobody thought to question, and a known problem gets managed while a problem hidden behind a green label does not.

This selective and green picture has consequences that go much further than how sustainability is measured, because the energy transition was expected to free the world from depending on a small number of countries for its energy, and it has reduced that dependency at the generation phase, but in doing so it has created a new one at the supply chain level that has received far less public attention, since this research found that China controls between 88% and 100% of the refining of the rare earth elements that wind turbines depend on, that the Democratic Republic of Congo supplies 74% of global cobalt, and that the average concentration across upstream mineral indicators reaches 83.8%, and what makes this more than a supply chain risk is what it reveals about the true cost of cheap renewable energy because that low price was only possible by pushing the real costs somewhere less visible, onto the environment of mining regions, onto communities that received little in return, and onto future generations who will deal with the waste, and the world built its energy transition on this price without asking who was paying the rest of the bill.

What makes this dependency even more serious is that the supplier the world depends on is itself not stable and this research found that one in three solar PV manufacturers is currently at risk of going out of business, that module prices fell by more than 25% in a single year, and that the investment needed to meet the 2030 targets is more than three times what is currently being used, which means the world has placed its energy future in the hands of a supply chain that is both geographically concentrated and financially fragile, and this is the connection that the sustainability label made invisible not just that the chain has problems but that the problems are growing at exactly the moment the world needs it most.

The NOOR Ouarzazate case study brought this into focus at the project level. The project overstated its annual CO2 avoided by 37%, it underestimated its water consumption by a factor of 3.4, and Morocco gave up land, water, and community resources to host one of the world's largest solar projects while sending 70% of the investment value to international suppliers, many of whom belong to the same financially fragile Chinese manufacturing sector that Chapter 3 identified as a risk for the entire transition, and this raises a question that the sustainability label applied to NOOR never answered: sustainable for whom? Brundtland (1987) defined sustainability as meeting the needs of the present without compromising the ability of future generations to meet their own but that definition was never meant to apply only to the countries that consume the clean electricity while the countries that produce the components bear the environmental and social costs without having benefit from the economic value, and what a growing body of research on energy justice has begun to show is that the communities that gave their land and minerals cheaply will not give them again on the same terms once they understand what they gave up, and the resistance to future energy projects that this could create may make the next phase of the transition far harder to build than the current one.

Before turning to what the survey adds, it is worth being precise about what kind of problem this research has actually identified, because three different claims are sometimes treated as the same and they are not, sustainability is measured incompletely, which is a problem of method; the incomplete measurement is then presented as if it were complete, which is a problem of communication; and the word itself is loose enough that it can be applied to almost anything without being technically wrong, which is a problem of definition, and all three are present in the renewable energy sector, but the most consequential is the first, because without complete measurement there is nothing honest to communicate and the looseness of the word becomes an opportunity rather than a limitation.

The survey results give a human dimension to what the data and the case study can only partially show, because before seeing any supply chain information 56.1% of respondents associated renewable energy sustainability with clean electricity and no emissions, and after reading three supply chain facts their ratings dropped significantly from 3.228 to 2.807, with 71.7% judging the label as only partially accurate once given even a brief look at what happens beyond the generation phase. What makes this finding important is that the drop occurred even among respondents who already informed themselves about sustainability , a small but visible drop, the people who actively engage with the concept and put it into practice in their daily lives and yet they had still not been exposed to supply chain information specific enough to change their view before the survey, which means the gap is not about whether people care about sustainability but about whether they were ever given the right information to form an honest judgment, and the answer this survey gives is that they were not. What 71.7% calling the label only partially accurate ultimately reveals is that the public's sense of what sustainable should mean doesn’t include what the sector has been measuring, people feel that a word promising so much should cover more than the moment the electricity is produced and this matters because the energy transition depends on public trust, and if that trust is built on a label that describes one stage of a four-stage chain, then as the supply chain reality becomes more visible the trust the transition depends on risks breaking in ways that would be more damaging than the honest and transparent communication that should have happened from the beginning.

What Seuring and Müller (2008) established about sustainable supply chain management goes exactly to the change needed: sustainability cannot be achieved when only one stage is evaluated or one dimension is measured, and what renewable energy needs is not a different label but a more complete one, one that starts at the mine and ends at the recycling facility, that accounts for the carbon in manufacturing and not just in operation, that measures who captures the economic value and not just how cheap the electricity is, and that gives the public the full picture rather than the most convenient part of it. The path toward this is not technical, the data exists, the methods exist, and as this survey showed, the public is ready to engage with the full picture the moment it is made available to them. What is missing is not the ability to measure sustainability honestly but the willingness to do so, and they deserve to have seen it sooner.

Chapter 7 : Recommendations

The findings of this research call for changes that are needed at several levels, and while the energy transition is a global challenge, the supply chain problems identified here are specific enough to suggest directions for those who finance, manage, and evaluate renewable energy projects.

The World Bank, the European Investment Bank, and the African Development Bank, all of which financed the NOOR project , currently accept environmental assessments that start at the project boundary and ignore the upstream supply chain entirely, and the most important change they could make is to require that any project seeking their green financing must show that its sustainability assessment covers the full chain from where the minerals were extracted to what happens to the equipment when it stops working, not just the phase where electricity is produced, and the EU Taxonomy for Sustainable Activities, which today evaluates renewable energy projects mainly on operational emissions, offers a natural place to make this requirement official by extending its criteria to include the supply chain as a whole.

For companies in renewable energy supply chains, the most urgent need is knowing where their materials actually come from, because 42% of global solar PV manufacturing carries forced labor risk and most buyers cannot verify this because no system exists that follows materials from mine to panel, and the EU Battery Regulation which already requires companies to show the origin of battery materials before selling in European markets offers a model that should be extended to solar panels and wind turbine components, making it mandatory for companies to show where their materials come from before they can sell in regulated markets, in other words, traceability should be taken into consideration.

For researchers, the gap this research found most limiting is not analytical but empirical, only 5 out of 94 indicators in this research's database cover the social dimension, because institutional sources simply do not collect this data, and what is needed is not more studies analyzing existing numbers but research that goes to the mining regions, talks to the communities, and builds the social picture that sustainability assessments currently leave blank.

Conclusion:

When a supply chain is called sustainable, the word should mean something , it should mean that every stage of that chain, from the first extraction of raw materials to the last piece of waste, has been evaluated honestly against environmental, economic, and social criteria, and that the chain passes that evaluation not just where it is strongest but across the full stages and this is the standard this research applied to renewable energy supply chains, and it is a standard they do not yet meet.

This does not mean the energy transition is wrong or bad, it means the conversation around it has been incomplete, and incomplete communications lead to incomplete decisions, and incomplete decisions leave problems invisible until they become impossible to manage, and the supply chain of renewable energy has problems that are real, that are growing, and that the sustainability label has made easier to ignore than to address.

What needs to change is not the technology but the honesty with which it is evaluated, because a supply chain that is genuinely sustainable is not one that performs well at the generation phase and hopes nobody looks too carefully at the rest, it is one that can be examined the same way at every stage, from the mine to the recycling facility, across all three dimensions, for every community it touches and every generation it affects.

The energy transition is necessary and urgent but necessary and sustainable are not the same word, and confusing them is not just about the word itself but a supply chain governance one, because what does not get measured does not get managed, and the generation phase of renewable energy speaks for itself loudly, in gigawatts and falling costs and record installations, but the supply chain behind it has been failing silently, and in supply chain management, what stays silent stays broken.

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Appendices

Appendix 1: Empirical Study Database

Block	Variable	Description
Identification	ID	Sequential record identifier (1 to 94)
	Year	Year of publication of the source
Source	Source	Source code (NSEFI-PV, GWEC-BCG, IEA-SC, IRENA-COST, IRENA-JOBS, EBRD-WIND, USGS-MCS, IPCC-AR5), full names in sources table
Classification	Theme	Main theme: Manufacturing, Minerals, RE_Performance, Supply_Gap, Social, Financial
	Sub_Theme	Detailed sub-theme (e.g. Market_Share, Cost, LCOE, Concentration)
	TBL	Triple Bottom Line pillar: Economic, Social, Environmental
	SC_Stage	Supply chain stage: Upstream, Midstream, Operation, End_of_Life
Measurement	Var_Code	Short code of the variable (e.g. cn_mod, lcoe_pv)
	Var_Label	Full English label describing what is measured
	Value	Observed numeric value
	Unit	Unit of measurement (%, GW, USD/kWh, year, etc.)

Table A. 1—Data dictionary of the database

ID	Year	Source	SC Stage	Var Label	Value	Unit
1	2023	NSEFI-PV	Midstream	Share of coal in electricity used for solar PV manufacturing	62	%
2	2023	GWEC-BCG	End of Life	Earliest year REE end-of-life recycling viable at scale	2026	year
3	2022	IEA-SC	Midstream	Energy cost differential: Europe vs China (PV manufacturing)	2	x higher
4	2022	IEA-SC	Midstream	CAPEX differential: polysilicon US/EU vs China	3	x higher
5	2023	NSEFI-PV	Midstream	PV production cost differential: Europe vs China	15	% higher
6	2022	IEA-SC	Midstream	Energy sector debt cost increase (post-pandemic)	30	%
7	2023	NSEFI-PV	Midstream	Solar module price decline (since early 2023)	25	%
8	2022	IEA-SC	Midstream	Corporate R&D share spent on renewables (2021)	9	%
9	2022	IEA-SC	Midstream	Global public energy R&D as % of GDP (2021)	0,04	%
10	2022	IEA-SC	Midstream	Global public energy R&D as % of GDP (1980 peak)	0,1	%

Table A. 2—Extract from the database

Source	Full name	Supply chain stage	Information provided	Data points
IEA-SC	IEA, Securing Clean Energy Supply Chains (2022)	Upstream, Midstream	Costs, R&D, market shares, carbon, labour, mineral	31
IRENA-COST	IRENA, Renewable Power Generation Costs (2024)	Midstream, Operation	Capacity, LCOE, cost vs fossils, fossil savings	25
GWEC-BCG	GWEC & BCG, Wind Supply Chain Mission Critical (2023)	Upstream, Midstream, End_of_Life	Wind manufacturing capacity, China shares, REE refining,	18
NSEFI-PV	SolarPower Europe & NSEFI, PV Supply Chain (2023)	Midstream	PV energy mix, prices, utilisation, EU financing gap,	11
EBRD-WIND	EBRD, Wind Supply Chain (2024)	Upstream	Balsa wood concentration, mining deforestation	3
USGS-MCS	USGS, Mineral Commodity Summaries (2024)	Upstream	Lithium mining country shares	3
IPCC-AR5	IPCC, AR5 Working Group III Mitigation (2014)	Operation	Lifecycle CO2 of wind vs coal	2
IRENA-JOBS	IRENA, Renewable Energy and Jobs Annual Review (2024)	Operation	Global renewable employment	1
Total				**94**

Table A. 3—Sourced used,suplly chain stage informed,and information provided

Appendix B: Noor Ouarzazate Case study Database

Block	Variable	Description
Identification	ID	Sequential record identifier (1 to 65)
	Phase	Project phase: Complex (whole site), Noor I, II, III, IV
	Technology	Technology used: CSP (concentrated solar power), PV (photovoltaic), or Mixed
Source	Source	Source code (FESIA-2014, NOORo-I-NTS, NOORo-II-NTS, NOORo-IV-NTS, Water-ESIA-2014, WB-ICR-2025, Laaroussi-2023), full names in sources table
	Year	Year of publication of the source document
	Evidence_Type	Nature of the evidence: ESIA-claim, ICR-result, peer-reviewed, etc.
	Page_Ref	Page or section reference in the source document
Classification	TBL	Triple Bottom Line pillar: Economic, Social, Environmental
	Stage	Supply chain stage: Upstream, Midstream, Operation, End of Life
	Theme	Topic (Land, Water, Employment, Capacity, Emissions, etc.)
Measurement	Var_Code	Short code of the variable (e.g. cplx_mw, dam_avg)
	Var_Label	Full English label describing what is measured
	Value	Observed numeric value
	Unit	Unit of measurement (MW, ha, Mm³/yr, jobs, million MAD, etc.)
Annotation	Notes	Contextual explanation or qualification of the value

Table B. 1—Data dictionary of the database

ID	Phase	Source	Stage	Var_Label	Value	Unit
1	Complex	FESIA-2014	Operation	Total planned capacity of Ouarzazate Solar Power Complex	500	MW
2	Complex	FESIA-2014	Midstream	Total project investment	28	billion MAD
3	Complex	FESIA-2014	Upstream	Total complex land footprint	3000	ha
4	Complex	FESIA-2014	Upstream	Initial land acquisition from Ait Ougrour collective	2500	ha
5	Complex	FESIA-2014	Upstream	Price paid for first 2500 ha land acquisition	25	million MAD
6	Complex	FESIA-2014	Midstream	Direct construction jobs (complex total)	2250	jobs (avg)
7	Complex	FESIA-2014	Operation	Direct operation jobs (complex total)	450	jobs (avg)
8	Complex	FESIA-2014	Upstream	Mansour Eddahbi reservoir avg annual contribution	420	Mm³/yr
9	Complex	FESIA-2014	Upstream	Reservoir water used for irrigation	180	Mm³/yr
10	Complex	FESIA-2014	Upstream	Reservoir water for drinking water	4	Mm³/yr

Table B. 2—Extract from the database

Source	Full name	Supply chain stage	Information provided	Data points
WB-ICR-2025	World Bank, Implementation Completion Report, Morocco Noor Solar Power Project (2025)	Midstream, Operation, End of Life	Capex, tariffs, ERR, generation, sales, jobs, local content, water use, repair outcomes	20
FESIA-2014	MASEN, Framework ESIA of the Noor Ouarzazate Solar Complex (2014)	Upstream, Midstream, Operation	Total capacity, investment, land acquisition, jobs, reservoir water allocation	11
NOORo-I-NTS	MASEN, Non-Technical Summary, NOORo I CSP project (2012)	Upstream, Midstream, Operation	Phase I capacity, land, water, waste, jobs, emissions, biodiversity	11
NOORo-II-NTS	MASEN, Non-Technical Summary, NOORo II CSP project (2015)	Upstream, Midstream, Operation	Phase II capacity, land, water, jobs, emissions, traffic	8
NOORo-IV-NTS	MASEN, Non-Technical Summary, NOORo IV PV project (2016)	Upstream, Midstream, Operation	Phase IV capacity, land, water, jobs, biodiversity	8
Laaroussi-2023	Laaroussi et al., Environmental impact of NOOR 1 on Southern Morocco (peer-reviewed, 2023)	Operation	Independent assessment of water and biodiversity impacts	4
Water-ESIA-2014	MASEN, ESIA of the water supply pipeline for the Noor complex (2014)	Upstream, Midstream, Operation	Pipeline water transfer to the site, construction jobs	3
Total				**65**

Table B. 3—Sources used,supply chain stage informed,and information provided

Appendix c: Concentration Analysis

Component Group	Var_Code	China Share (%)	Description	Source
Solar PV: Modules	cn_mod	70	China share of global solar module production	NSEFI-PV
Solar PV: Cells	cn_cell	80	China share of global solar cell production	NSEFI-PV
Solar PV: Wafers	cn_wafer	97	China share of global solar wafer production	IEA-SC
Solar PV: Polysilicon	cn_polysi	80	China share of global polysilicon production	NSEFI-PV
Wind: Turbines	cn_turb	60	China share of global wind turbine manufacturing	GWEC-BCG
Minerals: REE mining	cn_ree_m	62	China share of rare earth element mining	GWEC-BCG
Minerals: REE processing	cn_ree_p	92	China share of REE processing and separation	GWEC-BCG
Minerals: Neodymium refining	cn_nd	100	China share of neodymium refining	GWEC-BCG
Minerals: Dysprosium refining	cn_dy	88	China share of dysprosium refining	GWEC-BCG
Minerals: Graphite mining	cn_graph	77	China share of graphite mining	IEA-SC

Table C. 1—China Share Across Supply Chain Components

Stage	Avg China Share (%)	Min (%)	Max (%)	Components
Midstream (manufacturing)	77,4	60	97	5
Upstream (minerals/refining)	83,8	62	100	5
Operation (deployment)	65,3	61,2	69,4	2
OVERALL (all components)	**80,6**	**60**	**100**	**10**

Table C. 2—Concentration Summary bu Supply Chain Stage

Appendix D: Expert Interview – NOMAC:

Interviewee: Former Head of the Electrical Department, NOMAC (Noor Ouarzazate Solar Complex). Interview conducted in writing, originally in French; translated below. Used with consent for academic purposes.

Q1. Can you briefly describe your role at NOMAC?
At NOMAC, I was Head of the Electrical Department. My role was to supervise electrical maintenance activities to ensure the reliability, availability and safety of the installations. I was also responsible for planning and monitoring preventive and corrective maintenance operations on the main electrical equipment, as well as coordinating the technical teams and working with the other departments to keep the plant running properly.

Q2. In the Noor Ouarzazate project, where did the key components (solar panels, equipment, structures) mainly come from?
The main equipment and components of the project generally came from the suppliers who carried out the initial installation of the plant. In most cases these technologies were supplied by international companies. A large share of the equipment came from suppliers based in Spain, China and Germany, which are major players in the manufacturing of technologies and equipment for solar power plants.

Q3. Does the manufacturing of these technologies generate significant environmental impacts (for example emissions, energy consumption, raw material extraction)?
Yes, the manufacturing of these technologies can generate certain environmental impacts. The production of solar equipment requires raw materials, energy and industrial processes that can lead to greenhouse gas emissions and significant consumption of natural resources. However, despite these impacts at the manufacturing stage, renewable energy technologies generally allow a significant reduction of emissions across the whole life cycle compared with conventional energy sources.

Q4. In your experience, do renewable energy projects take these manufacturing-related impacts into account?
In my experience, renewable energy projects increasingly take these impacts into account, notably through environmental impact assessments and requirements linked to international standards. In practice, however, attention is often focused more on performance, reliability and cost of the technologies, while the environmental impacts linked to equipment manufacturing are sometimes less visible during the operational phase of the project.

Q5. Does the project depend strongly on imports for certain technologies or materials?
Yes, the project depends to a large extent on imports for certain key technologies and equipment. This concerns notably specialised equipment such as the generator, the turbine, pumps, transformers, and several pieces of equipment linked to the water-steam cycle. These technologies are generally supplied by international manufacturers with the necessary expertise and industrial capacity, which implies a strong dependence on international supply chains.

Q6. In your view, what are the main challenges in making renewable technology supply chains more sustainable?
The main challenges in making renewable technology supply chains more sustainable concern above all the origin of materials, the reduction of emissions linked to manufacturing and transport, waste management and end-of-life recycling of equipment, and coordination with suppliers that comply with strict environmental and social standards.

Q7. Do you think that renewable technology supply chains can today be considered truly sustainable? Why?
Today, renewable technology supply chains cannot yet be considered fully sustainable. Although efforts are being made to reduce the environmental footprint and improve social practices at some suppliers, many manufacturing and transport stages still have a significant impact. Full sustainability remains a goal to reach, in particular in terms of material traceability, end-of-life recycling, and emission reduction across the whole life cycle.

Appendix E: Triangulation Test – NOOR Ouarzazate

Theme	ESIA claim	Independent finding	Gap	Verdict
Water consumption (Noor I)	1.75 Mm^3/yr, no significant impact	6 Mm^3/yr, risk of conflict with irrigation	3.4x understated	Contradicts
Cooling design	Wet cooling appropriate	Noor II/III switched to air cooling	Design reversal	Contradicts
CO_2 avoided per phase	>1 Mt/yr per phase	808 kt/yr complex total (2019–2023)	~63% of single-phase claim	Contradicts
Generation output	Nameplate capacity assumed	739 GWh vs 1,144 GWh target	35% underperformance	Contradicts
Beneficiaries	>1 million people (Noor I)	1.3 M complex-wide vs 2.2 M target	59% of revised target	Partial
Operation employment	~240 jobs across 4 phases	234 jobs complex-wide (2022)	Within 3% of estimate	Confirms
Local employment	Local recruitment stressed	43% operation / 28% construction local	Modest local share	Partial
Domestic value capture	Not quantified, positive framing	~30% domestic, 70% offshore	70% offshore	Omitted
Tariff / cost	Tariff not disclosed	\$0.162/kWh; ERR -0.07% appraisal, 0.89% completion	Negative ERR	Omitted
Technical reliability	Technology proven, no failure modes	Noor III molten salt tank leaks, extended shutdown	Major failure	Omitted
Biodiversity	Low impact, few endemic species	Loss of native vegetation and habitat	Significance disputed	Contradicts
HTF / oil contamination	Risk managed by mitigation	Rainwater contamination risk flagged	Underweighted	Contradicts
Conflict with irrigation	Not raised, marginal water share	Conflict of use explicitly raised	Excluded	Omitted
Overall project performance	Success framing	WB rating: Moderately Unsatisfactory	Official downgrade	Contradicts

Table E. 1—Triangulation test

Appendix F: Survey Questions

1. What is your occupation?
Student / Supply chain or logistics professional / Energy sector professional / Sustainability or ESG professional / Other

2. What is your age group?
Under 25 / 25–35 / 36–50 / Over 50

3. In your opinion, what does the word "sustainable" mean?
Something that does not pollute during use / Something that balances nature, people and money / Something that uses renewable or natural resources / Something labeled "green" or "eco-friendly"

4. On a scale of 1 to 5, how sustainable do you think renewable energy is today?
1 (not sustainable at all) to 5 (completely sustainable)

5. When you think of renewable energy being sustainable, what comes to mind first?
It produces clean electricity with no emissions / It uses responsibly sourced materials / It is economically stable and affordable / I never really thought about it

6. Do you actively inform yourself about sustainable practices?
Yes, regularly / Yes, occasionally / No, not really / No, never

Information shown to the respondent ("Did you know?"):
— Most solar panels are manufactured in China, largely using coal-powered energy.
— The minerals needed for solar panels and wind turbines are often mined in regions with serious environmental damage and poor labour conditions.
— End-of-life solar panels contain hazardous substances (lead, cadmium) that can contaminate soil and water if not properly managed.

7. Do you put sustainable practices into place based on the information you have?
Yes, regularly / Yes, when possible / Rarely / No, never

8. Now that you know this, how sustainable do you think renewable energy really is?
1 (not sustainable at all) to 5 (completely sustainable)

9. In your opinion, is the word "sustainable" used accurately when describing renewable energy?
Yes, it is accurate / It is only partially accurate / No, it overstates the reality

10. In your opinion, what would it take for renewable energy to be considered fully sustainable across its entire supply chain?
(Open-ended)

11. In your opinion, what is the most urgent action needed to improve the sustainability of renewable energy supply chains?
Stricter regulations on mining and raw material sourcing / More transparency on where and how components are manufactured / Investment in recycling and end-of-life management / Diversification of production away from a small number of countries / Better working conditions in manufacturing regions

Appendix G: Survey Tests

Test 1: Paired-samples test of the perception gap (Q4 pre-stimulus vs Q8 post-stimulus)								
Measure 1	**Measure 2**	**Test**	**Statistic**	**z**	**df**	**p**	**Effect size**	**SE effect**
Q4 (pre)	Q8 (post)	Student t	4,261		113	< .001	0,399	0,12
Q4 (pre)	Q8 (post)	Wilcoxon	1950	3,85		< .001	0,526	0,136

Descriptive: Q4 and Q8

Variable	N	Mean	SD	SE	CV
Q4 (pre-stimulus)	114	3,228	0,799	0,075	0,247
Q8 (post-stimulus)	114	2,807	0,901	0,084	0,321

Table G. 1— Paired-samples Student t-test and Wilcoxon signed-rank test comparing the Likert score before (Q4) and after (Q8) the information stimulus.

Test 2 : Bivariate correlations across selected variables					
Variable 1	**Variable 2**	**Pearson r**	**p**	**Spearman ρ**	**p**
Q6 (inform)	Q4	-0,182	0,06	-0,16	0,097
Q6 (inform)	Q8	0,247	0,01	0,24	0,013
Q6 (inform)	Q7 (action)	0,358	< .001	0,308	0,001
Q4	Q8	0,234	0,012	0,215	0,021
Q4	Q7 (action)	-0,139	0,149	-0,163	0,09
Q8	Q7 (action)	-0,036	0,71	-0,036	0,709

Table G. 2—Pearson and Spearman correlations between Q4 (pre-stimulus Likert), Q8 (post-stimulus Likert), Q6 (how often respondents inform themselves about sustainability), and Q7 (how often they put sustainable practices into action).

Test 3 : Contingency table and Chi-squared test: Q5 (what comes to mind) × Q9 (is "sustainable" used accurately)				
Q5 (first comes to mind)	**No, overstates reality**	**Only partially accurate**	**Yes, accurate**	**Total**
Responsibly sourced materials	7	23	5	35
Clean electricity, no emissions	7	47	10	64
Economically stable & affordable	0	8	3	11
Never really thought about it	0	3	0	3
Total	**14**	**81**	**18**	**113**

Chi-squared test

Statistic	Value	df	p	N
χ^2	5,448	6	0,488	113
Contingency coefficient	0,214			
Cramér's V	0,155			

Table G. 3— Contingency table and Chi-squared test of independence between Q5 (what comes to mind first when renewable energy is called sustainable) and Q9 (is the word "sustainable" used accurately).

EXECUTIVE SUMMARY

Context: Renewable energy is widely described as sustainable and this label is usually examined during the generation phase where clean electricity is produced. As the energy transition accelerates, questions about what happens upstream in mining and manufacturing, and downstream at the end of life, remain unanswered in both academic research and public discussions.

Objectives: This research asks whether renewable energy supply chains are sustainable when environmental, economic, and social dimensions are considered at the same time across their full lifecycle, from raw material extraction to end of life management.

Methodology: A mixed methodology is adopted combining three independent layers of evidence. First, a quantitative analysis of 94 supply chain indicators drawn from eight institutional sources and organized across four supply chain stages using the Triple Bottom Line framework. Second, a case study of the NOOR Ouarzazate Solar Power Station in Morocco, triangulating 14 sustainability claims from official project documents against three independent sources including a World Bank completion report and an expert interview. Third, a perception survey of 115 respondents designed to measure how public understanding of renewable energy sustainability changes after exposure to supply chain information, analyzed using paired t-tests, Wilcoxon signed-rank tests, Spearman correlations, and chi-square tests.

Findings: The global supply chain analysis produces an overall Triple Bottom Line score of 1.75 out of 6, with three out of four stages failing or only partially meeting sustainability criteria. The NOOR case study confirms these patterns at the project level, with only 1 out of 14 testable sustainability claims independently confirmed and the project officially rated Moderately Unsatisfactory by the World Bank. The perception survey shows that after exposure to three supply chain facts, respondents' sustainability ratings drop significantly from 3.228 to 2.807 out of 5, and 71.7% judge the sustainability label as only partially accurate. Together these findings suggest that the word sustainable, as currently applied to renewable energy, describes the generation phase accurately and the rest of the supply chain incompletely.

MOTS-CLÉS/KEYWORDS: Renewable energy, sustainable supply chain management, Triple Bottom Line, lifecycle assessment, perception gap, energy justice, greenwashing.

NOMBRE DE MOTS/WORD COUNT: 20 363 words

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