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Review

# Assessing social impacts and Energy Justice along green hydrogen supply chains: a capability-based framework

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ABSTRACT

This paper presents a comprehensive and versatile framework for assessing the social impacts and energy justice concerns of green hydrogen supply chains using a capabilities and human rights-based approach. As global efforts to decarbonise the energy sector accelerate, green hydrogen emerges as a key component to replace fossil fuels, achieve energy security and meet climate targets. Despite its potential, the transition to a hydrogen economy must address significant social justice challenges, both in Europe and in the context of global trade. This study emphasises the significance of implementing energy justice principles, encompassing distributive, procedural, and recognition justice throughout the hydrogen value chain to ensure an equitable transition. The rationale for the selection of the relevant capabilities to be considered in the analysis of the social impacts of hydrogen penetration into European and international energy systems is discussed. Theoretical links between capabilities and human rights theories are drawn upon to reinforce the argument for selecting capabilities that may be impacted by hydrogen supply chains. The identification of socially relevant aspects is illustrated through a review of both technical and social science literature concerning green hydrogen supply chains. Moreover, empirical studies on subjective well-being provide a foundation for distinguishing between the maintenance (basic) and growth capabilities of individuals, enabling a hierarchical evaluation across a broad range of dimensions. Overall, the framework is conceived as a tool that can guide empirical research to assess the social impacts of energy transition scenarios, providing social sustainability indications to support policy design.

## 1. Introduction

A rapid decarbonisation of the energy sector is essential in order to meet the targets agreed by 196 countries at the United Nations Conference on Climate Change (COP21) in Paris in 2015 [1]. Many institutional actors, including the International Energy Agency [2], the European Union [3], the International Renewable Energy Agency [4] consider hydrogen a fundamental tool for decarbonising the economy, because, as an energy carrier, appears suitable to enable the transition from dispatchable fossil fuels to intermittent renewable sources of energy. In May 2022, the European Union issued the RePowerEU plan establishing hydrogen as one of the pillars to increase European energy security [5]. The EU goal is to develop renewable hydrogen, with the aim of producing 10 million tonnes domestically and importing 10 million tonnes by 2030. Renewable hydrogen - or "green hydrogen" - can be obtained via electrolysis using renewable electricity to split water into hydrogen and oxygen. In official taxonomies, such as in the EU Renewable Energy Directive (Art. 2.36), hydrogen and its carriers obtained combining renewable hydrogen with other molecules (for example ammonia, liquid organic hydrogen carriers, synthetic methane), are referred to as 'renewable fuels of non-biological origin (RFNBO). In this work, we use the term hydrogen to encompass all RFNBO. According to the European Commission, hydrogen will play a key role as an energy carrier and in decarbonising sectors where other alternatives might be unfeasible or more expensive. Green hydrogen can be used to replace fossil fuel in a wide portfolio of products and services, including fertilizers, refineries and chemicals, steel, power and heat generation, and transport, to name a few. Renewable hydrogen can be produced at times when solar and wind energy resources are abundantly available, providing long-term and large-scale storage to support the

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EU's electricity sector. The storage potential of hydrogen is particularly beneficial for power grids, as it allows for renewable energy to be preserved not only in large quantities but also for long periods of time. This means that renewable hydrogen can help improve the flexibility of energy systems by balancing out supply and demand, helping to boost energy efficiency throughout the EU [5]. The establishment of a global market for clean hydrogen requires, among other factors, the development of new supply chains. Deciding which direction to take is a matter of intense stakeholder debate. Stakeholders include governments, renewable electricity suppliers, industrial gas producers, electric utilities, car manufacturers, oil and gas companies - and others [6]. According to Lindner (2023), factors such as the quality of democracy, human rights and government accountability appear to play a marginal role in policy-making in most green hydrogen collaborations between countries of the global North and South.[1] In fact, based on literature findings [12], the most significant impacts can be observed in the context of extra-UE long supply chains.

The discourse from governments, corporations, institutions, and researchers often revolves around the "transition to a low-carbon economy" without addressing the aspects of justice, nonetheless this issue is a crucial factor in the transition outcomes [13,14]. On the contrary, our approach acknowledges that the mainstream economic approach has failed to deliver inherently 'just' outcomes for society and has proved unable to significantly address the increasing societal inequality. This can be ascribed to the dominance of neoclassical economic thought, which continues to inform economic policymaking [15].

In light of the aforementioned considerations, this article aims to develop a framework that is flexible enough to analyse social impacts, assess their costs and benefits, and inform policy choices. In order to do so, it employs a capability approach [16,17] to delineate the social domains that are of most interest in the assessment of the social impacts of hydrogen. In the following sections, after discussing the place of hydrogen in the energy transitions and introducing the social impacts of hydrogen, a framework for the evaluation of social impacts of hydrogen is proposed that outlines specific capability domains to be considered. For each of these domains, certain capabilities are proposed that are considered suitable for assessing the social impacts of hydrogen through the different contexts of its supply chain. To construct this framework, we relied on human rights literature [18–20] and empirical studies on subjective well-being [21–23].

## 2. The place of hydrogen in the energy transition

Hydrogen can be produced through many processes that use different energy sources. Thermochemical and biochemical processes use hydrocarbons or other organic molecules as material sources for hydrogen. Electrochemical and photochemical processes use water as a source [24]. In general, each production method is associated with a colour-based label indicating a different set of energy sources and production methods [25]. For example, *grey hydrogen* is produced from natural gas through steam methane reforming (SMR), and it is linked with high $CO_2$ emissions, while *blue hydrogen* also uses the same source (natural gas) and the same method (SMR) but adds carbon capture and storage (CCS) in the process to reduce emissions. Among the different types, *green hydrogen* stands out as the most promising solution oriented towards a carbon-neutral future [25,26] and, thus, represents the main focus of our interest. *Green hydrogen* is primarily produced from water electrolysis powered by renewable electricity sources such as solar, wind, or hydro, resulting in zero direct emissions. Beyond electrolysis, additional - and way less common - methods for green hydrogen production include solar-to-hydrogen technologies (*photohydrogen)* and biological processes using algae and bacteria (*biohydrogen)*. In this contribution we will focus on water electrolysis because at present it remains the most relevant, widespread and commercially viable method for industrial green hydrogen production. In a 2023 dedicated report, the IEA proposed a classification system based exclusively on the emission intensity of hydrogen production, to overcome the colour-based labelling system in the direction of greater transparency and interoperability. In this paper we refer to the colour-label of "green hydrogen" to indicate hydrogen produced via electrolysis powered by renewable electricity, with no direct emissions [27].

To better understand the full scope of the new green hydrogen transition we must start by discussing several structural elements. Adopting a life-cycle perspective, all the green hydrogen-related processes - starting with the extraction of raw materials and up to its disposal, encompassing the production, transport and final consumption phases - should be taken into account.

The production of green hydrogen requires electrolysers, purified water and renewable electricity. It is important to point out that green hydrogen production directly depends on the production of the renewable energy needed to operate the electrolysers. Therefore, a major contribution to sustainability challenges will come from the expansion of renewable energy generation capacity. The social and environmental impacts of renewable energy generation are addressed by a large body of literature, which has been used to review some of the social issues related to the sustainability of green hydrogen [33,34]. The potential impact of renewable energy on local communities, habitats and wildlife can vary greatly depending on the design of the facilities and the locations where they are proposed. It is important to note that while some critical environmental issues may not directly affect social aspects, the long-term degradation of ecosystems can have significant social impacts. Other potential risks may arise at the upstream stages of the green hydrogen supply chain: the manufacture of renewable energy production devices (photovoltaic panels, wind turbines, etc.) may be associated with poor working conditions or health hazards. Furthermore, the extraction of materials, in addition to the previously mentioned risks, may also result in land and water grabbing, and conflicts over the control of mines or transport routes.

Once produced, hydrogen is stored and transported as a compressed gas in tanks or pipelines, as a liquid in cryogenic tanks, or in specific chemical carriers like ammonia or methanol. The main final uses of hydrogen concern mainly industrial applications (e.g., in refining, steelmaking or in fertilizers production), power generation and storage, and in different transports application (e.g., in a variety of fuel cell electric vehicles or as a component for e-fuels).

With regard to hydrogen use and applications, four main areas can be identified. These include the use of hydrogen: a) as a feedstock for industrial processes (e.g., in steel production, refining and chemicals production); b) as a fuel for transportation (e.g., in cars, trucks and trains but also for aviation and ships); c) for use in residential or industrial buildings (e.g., for heating or cooking) and d) as an energy storage and power generation technology [24,28]. In 2022, global hydrogen use reached 95 Mt. and was dominated by the chemical (ammonia production) and oil refining sectors, while low-emission hydrogen supply accounted for only 0.7 % of global hydrogen production and use [2]. The uptake of hydrogen in innovative applications relevant for decarbonisation targets (e.g., in heavy industry, transport, production of hydrogen-based fuels or electricity generation and storage) accounted for less than 0.1 % of global demand [2]. Although hydrogen production is still dominated by the unabated use of fossil fuels, decarbonisation policies aim to drive it away from the fossil-based processes towards low-emission hydrogen systems. Electrolysis powered by renewable energy appears to be the most promising way forward. To date, there is broad consensus that green hydrogen is a key tool for decarbonisation

[1] Official documents from the UNDP provide a definition and list of Global South countries. The concept of Global North-South exchanges is central to the "Unequal Exchange Theory" [7], which has also been incorporated into the field of Ecological Economics, where it is referred to as "ecologically unequal exchange" [8–11]. Similarly, the term 'green colonialism' is also being used in this context.

and 41 governments have set official hydrogen strategies, raising their ambitions with each update [2].

The European Union's RePowerEU plan sets ambitious targets for the domestic production and import of renewable hydrogen by 2030, aiming to enhance energy efficiency, diversification and security. At this stage, the public and private sectors are converging in a commitment to long-term investments in the low-emission hydrogen sector. The International Energy Agency's Net Zero Emissions by 2050 Scenario (NZE Scenario) requires 41 USD billion of investment on electrolysers installations by 2030, confirming that an exponential growth is needed to meet the climate targets [29]. According to the latest IEA's NZE Scenario, clean hydrogen use is expected to grow by 6 % annually, reaching more than 150 Mt. of hydrogen use by 2030, with nearly 40 % of this used in new applications and more than 70 % produced by electrolysis [29]. The EU Hydrogen Strategy (COM/2020/301) foresees that from 2030 to 2050 hydrogen technology will be mature and deployed on a large scale in almost all sectors of the economy, with some projections indicating that green hydrogen will constitute at least 14 % of total energy consumption by 2050 to meet decarbonisation targets [30].

Recent research has argued that the use of green hydrogen can facilitate the fulfilment of multiple Sustainable Development Goals [31], the most evident example being the SDG7, which is oriented to "affordable and clean energy" [32]. In fact, as is frequently asserted, investment in green hydrogen could drive industrial and technological development in the global economy by creating skilled jobs, reducing unemployment and stimulating economic growth, thus expanding beyond the borders of environmental sustainability beyond its immediate scope.

## 3. Introducing social impacts of hydrogen

Hickel et al. [10] demonstrate that the workforce of the Global South is responsible for an astonishing 90 % of the labour power that drives the world economy, yet receives only 21 % of global income. The findings demonstrate that the international exchange of labour is, in fact, uneven. This disparity helps to elucidate why, despite the advent of a "global wealth explosion" driven by trade and technological advancement, a considerable number of nations in the Global South continue to experience elevated rates of poverty. For example, in 2021, wealthier countries imported 906 billion hours of embodied labour from poorer countries. This is defined as the total amount of labour required to produce a good or offer a service from start to finish. In return, they exported a mere 80 billion hours of labour, encompassing both low-skilled work in sectors such as agriculture and high-skilled labour in sectors such as computer engineering. As Hickel elucidates, this ultimately equates to 826 billion hours of net labour extracted from the Global South, which is greater than the total hours provided by the combined workforce of the United States and Europe. If workers in the Global South were remunerated at a rate commensurate with their counterparts in the Global North, the value of those hours would be approximately $18.4 trillion. However, the team observed that wages in the South are between 87 % and 95 % lower for work of equal skill. It is probable that the green hydrogen supply chain will serve to reinforce these trends.

In order to ensure that the transition to hydrogen is not constrained to the technocratic sphere, it is necessary to accelerate and expand research efforts into its social impact [34,35]. Currently, social science research on green hydrogen tends to focus on public perceptions and acceptance. However, further challenges can be identified [36–38]. For instance, there is a significant lack of in-depth research on the impact of hydrogen production, and the underlying renewables energy generation, on local communities and indigenous peoples, the impact on the current and future labour market, the social impact of water consumption required by electrolysers and the opportunities and risks regarding energy independence. In a systematic assessment of 28 countries in the Global South, Tunn et al. [39] identified the socio-ecological risks associated with green hydrogen. Their findings indicate that these countries face considerable challenges related to energy, land, and water. Additionally, the current governance of green hydrogen may intensify the economic dependencies of these countries on the Global North. In this sense, a set of sustainability criteria has recently been proposed to analyse green hydrogen projects based on six impact categories: energy transition, environment, basic needs, socio-economy, electricity supply, and project planning [40]. Blohm and Dettner [40] suggest that social science can develop a theoretical framework suitable to identify a hierarchy of priorities among the criteria, which can serve as a guide for assessing the sustainability of hydrogen projects. One of the dimensions of sustainability is the social dimension, and equity is a key element of the decarbonisation pathway. Indeed, it must follow principles of equity and fairness for both individuals and communities, linking different scales of reality - local and global [15]. This is particularly important in relation to major issues of global justice such as income, gender and ethnicity, both in the global North and South [15,39]. Principles, instruments, criteria and agreements are needed to ensure fairness and equity for all individuals and social groups. In this matter, the concept of a just transition brings together concerns about the environment, climate, energy poverty and social justice. In fact, the transition to a zero-carbon economy could imply social costs connected to the construction of new infrastructures, the necessity of raw materials, the accessibility of energy services and the overall distribution of benefits and ills, which, without socially equitable policymaking, risk of increasing economic inequality rather than diminishing it [14]. In this sense, some scholars have suggested that just transition and energy justice are rooted in a principle of equality and that this may make it easier to evaluate the outcomes of energy justice policies [41]. Szulecki proposes an analytical framework with the aim of establishing energy justice as a conceptual and decision-making tool towards the ideal of [24] [42]. This is achieved by operationalising the concept with specific indicators to allow for comparisons and designing policy change. The present article adopts a different perspective with the aim of formulating a theoretical model to assess the social impacts that the deployment of hydrogen-related technologies and projects might cause during such a transition.

To this end, energy justice principles [43] provide a framework to define relevant social indicators and assess social impacts of green hydrogen life-cycle - as the challenge of energy justice is to apply this approach across the whole energy system [44]. In fact, potential impacts and injustices may be distributed along the hydrogen value chain, and some efforts to map them have already been made [45–47]. The impacts associated with land use, water, local resources, and end-of-life materials are identified in the literature. Further, the risk of green colonialism, where developed nations see developing nations solely as a source of raw material, is discussed by scholars [48]. Carlson and Trencher [49] propose a framework for assessing 'decarbonisation risks' based on seven categories: geophysical, environmental-ecological, technological, economic, socio-cultural, institutional and geopolitical. This framework considers the entire supply chain and competition between different end uses. In fact, the current phase represents an early phase in the development of a hydrogen economy. In accordance with the preceding proposal, the present one aims to contribute towards a just transition by means of an overall framework that would enable the assessment of social impacts, both negative and positive, and that could influence the direction of green hydrogen development towards a just transition. Nevertheless, a capability-based approach was selected in the present study. Indeed, the primary objective of this framework is to shed light on the manner in which green hydrogen can influence individuals and social groups, and their access to a life of dignified existence.

## 4. Defining Energy Justice: a capability approach

### 4.1. Energy Justice

The concept of «energy justice» has its roots in the broader debate on environmental justice [50], which has been ongoing in the United States since the 1970s. Energy justice calls on the research community to address concerns about the equitable treatment of different populations, social groups and nonhumans in relation to the externalities of infrastructure siting and energy production [41]. Green hydrogen production is seen as a tool to decarbonise current industrial processes. However, its implementation can be an opportunity to influence both industry and society, and to address potential injustices along global supply chains. When energy justice is applied to green hydrogen, it is necessary to address concerns from production to final use, including social issues related to raw material extraction, infrastructure siting, pricing and consumption. In light of this, it is necessary to incorporate an idea of justice that adequately takes into account previous structural injustices, promoting inclusive governance on a global scale, from the arenas of the hydrogen economy to the empowerment of local communities [47,51]. In fact, the energy transition has the capacity to exacerbate existing socio-economic inequalities [52], resulting in the reinforcement of elitism, discrimination and the concentration of wealth [53].

Jenkins et al. [44] promoted a «whole systems» approach to improve the identification of potential externalities and otherwise unintended consequences by shifting the focus to a global scale. In fact, social impact assessments and energy policies often deal with only one aspect or geographical scale of an energy system, thus neglecting overall impacts and effectiveness. A whole-systems approach involves identifying the characteristics of the system elements and examining the interactions between them. Firstly, the assessment of energy justice throughout the supply chain enables the assessment of the full socio-environmental cost of an energy source. Secondly, such assessment could affect the choice of an energy source over others and, ultimately, energy security [54], which entail elements of availability, affordability and sustainability [55].

Given that the green hydrogen economy is still in its infancy, the analyses that can be conducted are necessarily predictive in nature and draw on previous research on energy justice. In their analysis of the potential injustices of the hydrogen economy, Dillman and Heinonen [45] identified that these injustices manifest throughout the value chain, from decision-making and production to utilisation. In this context, it is essential to explore the connection between green hydrogen development and the three tenets of energy justice [43]: distributive, procedural and recognition. Moreover, the notion of restorative justice needs to be taken into account [56,57].

The analysis of current collaborations between the Global North and the Global South reveals a critical issue: the equitable development of energy systems in the Global South is subordinated to the economic interests of stakeholders, particularly corporations, in the Global North [58]. In this context, studies indicate that the emergence of a green hydrogen economy, along with the concomitant growth in renewables energy, is likely to intensify green extractivism and perpetuate socio-economic injustices that burden marginalised populations in Global South countries [33,39,59,60].

Dillman and Heinonen [45] address the distribution of social benefits derived from green hydrogen production, advocating for the redistribution of these benefits or the establishment of new forms of community ownership in green hydrogen production. They emphasise the necessity to avoid increasing costs for consumers or to disadvantage alternative technologies in the transition. From the procedural justice perspective, adequate consideration of factors such as political systems, civil rights and institutional stability is a prerequisite of a feasibility study. The reduction of these aspects to the single concept of "investment security" can result in the development of projects in authoritarian countries [58]. In the green hydrogen project, transparency of information and involvement of local communities in the decision-making process are key to achieving procedural justice [45]. The concept of procedural justice entails the existence and efficacy of grassroots institutions, such as trade unions, organised communities and workers' collectives, which are capable of confronting the promoters of the project. The absence of collective action results in the reduction of procedural justice to a limited number of surveys and focus groups with individuals involved as a statistical representation of the target population. Furthermore, local institutions are often uninterested in highlighting critical aspects of the project. In discussing this specific form of justice, it is often the case that the process properties, the agency of participants in terms of power, and the actual impact of local agents in defining the project are overlooked. It can be argued that the interconnections between distributive, recognition-based and procedural justice, which are central to understanding the emergence and perpetuation of injustice, are often underconceptualised. This can be defined as a lack of investigation into the reciprocal influence of these concepts [61]. The recognition justice tenet leads researchers to consider which sections of society are ignored or misrepresented. There have been previous instances of energy infrastructure development that have resulted in the violation of the rights of indigenous peoples and local communities, particularly with regard to the use of land and water resources [58,62–64]. Energy justice assesses where injustices occur, which affected sections of society are ignored, and what processes exist for remediation, to identify and reduce such injustices [44].

The evaluation of energy injustice is to be integrated with the objective of rectifying the harm inflicted upon individuals, society, and the natural world. This objective is encapsulated within the conceptual frame of restorative justice. Additionally, restorative justice can play a crucial role in identifying the areas where prevention strategies are required [56]. Therefore, the implementation of restorative justice in the context of green hydrogen development is proposed as a means of ensuring that decision-making processes take into consideration the potential harm and true cost of the decisions made. Van Uffelen proposes a proactive conception of restorative justice which can inform a just compensation system [57]. Similarly Corvino et al. [65] propose a capability approach towards the compensation of community disutilities generated by energy infrastructures. Such a system would ensure that individual households are consistently compensated for fear, risks of harm, and actual harms. It would also ensure that hydrogen-related distributive injustices and benefit distribution are addressed. The Proactive Conception posits that concerns regarding causality in decisions regarding compensation for damages can be superseded by considerations of stability, equality, and well-being [57].

In this spirit, the objective of the present paper is to analyse energy justice in the context of green hydrogen life-cycle. Meeting the challenges of a just transition requires a comprehensive account of social, economic and environmental impacts. And this is only possible by assessing the multiple places in a global energy chain where injustice can be found. In order to underpin evaluations of the energy justice profile of green hydrogen, the next sections are devoted to developing a theoretical framework that allows to assess the social impacts along its supply chains.

### 4.2. Bridging energy justice and impact assessment through a capability approach

In order to build a framework for the analysis of the social impacts of green hydrogen supply chains, we decided to adopt the Energy Justice framework as a reference. However, the informational bases of evaluations based on different categories - such as the individuals' goals pursued, the means to achieve them, or the freedom to achieve them - can lead to different, or conflicting results.

For that reason, we have grounded our framework in a vision that focuses on social impacts affecting individuals, whose needs and related capabilities are empirically based and hierarchically ordered. This approach developed first elsewhere [66] maintains that cross-cultural surveys [38,39] have empirically established the presence of needs whose relative importance changes modestly in relation to geographies and cultural contexts. Such needs can be interpreted as capabilities as Sen maintains [67]. As argued [66], shifting the emphasis from needs to capabilities could redirect attention from the motivations behind individual actions to the ability to fulfil those motivations; as it was maintained [66], the satisfaction of needs primarily hinges on fulfilling a purpose, while the ability to satisfy a need (capability) represents a condition that has the potential to achieve that purpose (the satisfaction of the need), without assuming that this outcome is guaranteed.

The capability approach provides instruments to operationalize the ideas developed in the field of energy justice and this approach has been earlier advocated for [66,68]. The capability approach has been employed to evaluate a variety of aspects of human well-being, including inequality, poverty, the well-being of individuals, and the average well-being of group members. It serves as a basis for evaluating policies and proposing changes to improve social conditions [69]. The capability approach can convey a social and political understanding of specific issues and impacts on the well-being of human beings. In particular, it can bridge the theories of energy justice with the more concrete aspects of policy-making and energy systems [70,71]. A green hydrogen supply chain can be developed within a single region or in a single country, but it can also extend across many different countries. Thus, our research deals with the issue of developing a framework that can adapt to different scales and contexts. In this respect, the capability approach enables comparative analysis across diverse contexts, thus advancing the understanding of distributions and inequalities across varying scales, from local to global [69,72]. Amartya Sen [17] and Martha Nussbaum [16] have developed a capability approach which considers a set of individual capabilities as an indispensable part of an evaluation of human development. This approach redefines human well-being as a multidimensional concept. A set of capabilities is necessary for people to realise their potential according to their own aspirations. Capabilities reflect combinations of functionings achievable by a person. Functionings are various "doings and beings" that an individual manages in their life [17]. Therefore, capabilities refer to «the substantive freedom to achieve alternative functionings combinations» [73]. However, Amartya Sen does not define a set of capabilities to leave ample room for adaptability to specific contexts. Conversely, Marta Nussbaum [16] posits the question of which fundamental capabilities a society should prioritise in its pursuit of human flourishing. On the one hand, any set of capabilities can allow meaningful comparisons between different regions and different contexts. On the other hand, in the case of a public policy that aspires to equitable outcomes, we must focus on identifying which areas are so central that their removal would deprive human life of dignity [16]. Thus, Nussbaum identifies ten central capabilities that every political system should guarantee as the bare minimum: Life; Bodily Health; Bodily integrity; Senses, imagination, and thought; Emotions; Practical reason; Affiliation; Other species; Play; Control over one's environment [16]. However, Robeyns [69] points out that in Sen's account, determining which capabilities to prioritise is a task for democratic decision-making. It is not possible to provide a single definitive list of capabilities, as different contexts and goals require different sets of capabilities. Therefore, the choice of capabilities depends on the specific purpose they serve, and different purposes may require their own different lists.

These studies have evidenced that this approach functions mainly as a conceptual framework, with considerable flexibility and versatility in its application [74–79]. This makes it a useful tool for assessing the impact of an intervention. Using this framework, Velasco-Herrejon and Bauwens [71] proposed a participative bottom-up capabilities approach to recognise the perception of justice and injustice of individuals neighbouring wind farms. In this manner, they illustrate the concrete meaning that the concepts related to the three tenets of energy justice have for people on the ground. While this approach has clear advantages, it is not without limitations. It is particularly well suited to analysing limited and circumscribed case studies. However, if the aim is to develop a framework that can serve as a guide to interpreting the inequities and impacts that may be generated in the different contexts by the green hydrogen supply chain, the capabilities framework should be developed in such a way that it can offer more general guidance to social impact assessment. This approach, hence, would have to start from general foundations. However, a bottom-up approach may prove useful when considering case studies where the reference context can be delimited. In such cases, a participatory approach may allow for considering the capabilities deemed important by the individuals belonging to specific contexts. For example, Clark et al. [80] propose a novel perspective on critical infrastructure, adopting the capabilities approach to human development as a theoretical framework. The framework utilised by the aforementioned researchers places greater emphasis on the services that infrastructure provides, as opposed to its physical condition or vulnerability.

It should be noted, however, that the capabilities approach has been subject to criticism for its individualistic orientation and perceived limitations in accommodating collective action, which is often regarded as the most effective strategy for countering prevailing market forces. The concept of "collective capabilities" appears to be more closely aligned with the notion of collective action, which is a crucial feature of justice. The notion of "collective capabilities" has gained considerable traction among capability approach scholars, who have emphasised the role of collectives in enhancing people's lives [81–83]. The concept of justice is not merely an individualistic or statistical phenomenon, as postulated by Rawls within the liberal paradigm of justice. Rather, it is concerned with the social capacity to facilitate the self-realisation of individuals within the process of socialisation. This implies that the individual is the product of a process of individualisation that is both psychic and collective. It is a social becoming that identifies itself in "collective units", parallel with the singular individualisation of each subject.

### 4.3. Human rights and capabilities

In Sen's view [17], the capability approach had to be kept non normative to allow for a flexible approach to different contexts where public reasoning and social discussion could agree on the central capabilities to be researched. Nussbaum employs a distinct methodology, identifying ten fundamental capabilities that all political systems must guarantee. Nussbaum's approach is based on an essentially philosophical rationale, offering a high degree of generality but also presenting challenges when attempting to operationalize it. Nevertheless, Nussbaum herself underscores the intimate connection between capabilities and human rights [84,85]. In Nussbaum's conception, capabilities are understood as the ability to realise functionings, which to be fulfilled assume the necessity of a role of institutional actors, such as governments, and thus are underpinned by established notions of human rights. Building on the analysis of the links between the capability approach and human rights in the work of Sen and Nussbaum, Vizard [20,86] proposed a "human rights-based capability framework". Indeed, it is argued that human rights can provide a minimum core for a list of capabilities that can evolve to address different applications and purposes, and it would be justified by an international consensus-building process [20]. Therefore, in the "Human Rights-Based Capability Framework", the choice of core or basic capabilities is justified by human rights theories. For instance, the Universal Declaration of Human Rights [87] could serve as a foundation for identifying and justifying a relevant capabilities set. In fact, international human rights standards are seen as evidence of a socially agreed value ordering. This approach is also based on international processes that are at least partly democratic and deliberative. However, Burchardt and Vizard [19] recognise some limitations of this approach. They argue that participation in the setting of human rights standards is a key concern and that the list of capabilities may be too general. Indeed, Vizard and Burchardt show that the human rights oriented selection of capabilities could be complemented with a process of deliberative discussion, giving the general public and those at risk of discrimination and disadvantage a role to identify and justify the selection of core and essential capabilities. This approach inspired the British EHRC Measurement Framework for Equality and Human Rights [88]. The authors of this framework emphasise the importance of combining legal evaluations with analyses of actual outcomes in monitoring equality and human rights. In this sense, the capability approach is proposed as a theoretical foundation for the evaluation of human rights. Indeed, the capability approach emphasises the significance of integrating an outcome-oriented assessment of individuals' substantive freedoms, encompassing both "doings and beings", with information concerning formal human rights commitments [88]. In this section, we show how the relationship between human rights and capabilities can provide tools for assessing policy outcomes in terms of both substantive freedoms and economic and social rights. Building on this, we aim to develop a theoretical framework for assessing the impact of green hydrogen through a list of capabilities that find their foundation in the Universal Declaration of Human Rights [87] and in the European Union Charter of Fundamental Rights [89]. In this way, we identified domains of capability that have general foundations and can thus guide the analysis of impacts in different contexts. Indeed, these domains offer a comprehensive overview of the potential implications of green hydrogen supply chains, and are also adaptable to the diverse geographical and social contexts in which we anticipate their application. On the one hand, the UK Equality and Human Rights Measurement Framework has served as a source of comparison and inspiration. On the other hand, it can be reasonably assumed that the framework presented in this study is as well-founded as it is further corroborated by other scholars' researches. Having established the general framework of our impact assessment, our subsequent research will employ empirical and participatory methodologies to modify and integrate the set of relevant capabilities. In the next session, we will utilise empirical results from the subjective well-being field to refine our framework by including informative distinctions.

### 4.4. Hierarchy of needs and capabilities

The capability approach was developed in parallel to a view of human well-being in terms of fulfilment of basic human needs. Sen argues that viewing individuals solely through the lens of their needs may provide us with a limited perspective on humanity [67]. This perspective «focuses on human beings as needy creatures, whereas the capability approach concentrates on the "freedom" that human beings can enjoy and have reason to value» [73]. Sen [90] acknowledged that capabilities are essentially an interpretation of needs. Analysing Martha Nussbaum's explanation of central capabilities, Gillian Brock [91] shows how in Nussbaum's theory capabilities and needs are closely intertwined. In fact, promoting capabilities and facilitating individuals in meeting their needs are closely linked. In making this connection, our concern is to find categories of analysis that allow for convenient operationalisation. In fact, assessing capabilities presents a challenge for indicators because they frequently depend on data that reflects end results rather than measuring inherent abilities and potential [66]. Inspired by Maslow's hierarchy of needs, it has been proposed elsewhere to move away from a horizontal approach to capabilities and prioritise those most important for human well-being [66]. Although empirical research generally has produced mixed results regarding the structure of the needs categories of Maslow's theory, it appears to confirm a general hierarchical structure of needs in the perception of well-being [21,22,92,93]. Cross-cultural surveys [21,22] demonstrated a positive correlation between the fulfilment of basic and psychosocial needs, namely "social support" and "respect", and subjective well-being. The relative importance of these needs remains consistent across different geographical regions. In light of the empirical evidence, some scholars put forth a proposition to categorise the needs in two distinct hierarchically ordered categories: namely, "maintenance" and "growth" [23]. Maintenance needs are those that are physiological and security-related, and they are essential for the organism's survival. Growth needs, on the other hand, include those related to belongingness, esteem needs, and self-actualisation, which are considered to be part of Maslow's hierarchy of needs [23]. Addressing the issue of energy poverty, Pellegrini-Masini [66] proposed to translate these findings into the area of capabilities. Due to the context-sensitivity inherent in the capabilities approach, the classification of central capabilities into the two categories may vary. A comparable approach was undertaken by Clark et al. [80]. In this article, we propose this idea with a different capabilities set. Indeed, we aim for an analysis framework that can capture the fundamental issues in a variety of different circumstances. This feature may prove beneficial in the context of the green hydrogen supply chain, given the variety of different possible geographical and technical configurations. For example, the analysis of the impact of renewable energy production in a rural area with a low population density may be based on different capabilities and different categories of maintenance or growth with respect to a densely populated area of a metropolis. Therefore, in the next session we intend to define capabilities in a way that is more appropriate to the study of the social impacts of the hydrogen supply chain in different contexts and scales.

## 5. A capability-based assessment framework

This section is dedicated to the development of a capability-based analytical framework suitable for assessing the social impacts of the adoption of green hydrogen as an energy carrier. To achieve this task, we take advantage of the context-sensitive nature of the capability approach, choosing the set of capabilities that enable us to better capture the main potentials and criticalities of the green hydrogen socio-technical system development. In the second section, we reported on the main potential social issues related to the development of hydrogen supply chains in the context of European decarbonisation targets. Two indications emerging from this review need to be considered. On the one hand, these aspects may concern very different geographical and socio-cultural contexts, as well as different stages of the green hydrogen life cycle. Indeed, we intend to consider the social implications of a) raw material extraction; b) construction and operation of renewable energy facilities; c) construction and operation of electrolysers; d) hydrogen storage and transport facilities and e) final use. Depending on the specific scenarios considered, these supply chain building blocks may be located in different regions, countries or continents. The framework aims to consider how the green hydrogen supply chain may impact on different social domains: distribution of significant resources, health and safety, economic activities and employment, human rights of the populations involved, political rights and democratic participation, socio-ecological assets preservation and educational opportunities. Building on what was discussed in Section 4.2, in this section we will define a set of capabilities. As mentioned in section 4.3, the choice of the capabilities to be included in the framework was also inspired in particular by the literature that linked the capability approach to human rights protection. We draw inspiration from the domains used in the UK EHRC's Equality and Human Rights Measurement Framework [88] to propose the inclusion of the capabilities within six domains of potential impact. The capabilities associated with each of these domains are inspired by several articles of the Universal Declaration of Human Rights [87] and of the Charter of Fundamental Rights of the European Union [89]. In this way, we intend to assess the social impacts of green hydrogen in terms of fundamental human rights underpinning capabilities. Utilising the established human rights declarations as a guideline, the selection of relevant capabilities is informed by empirical data derived from international surveys, which have identified a series of needs that are considered to be relatively universal [21,22]. Moreover, the selection is also informed a synthesis of expert knowledge and literature review on hydrogen and renewable energy systems. It is our understanding, based on the foundation outlined above, that the domains and capabilities that are likely to be able to detect significant social impacts have emerged.

The number of the capabilities to be included in the evaluation framework has been determined by balancing two principles: the first is that of completeness and the second is that of parsimony. In other words, we selected a number of capabilities that could sufficiently approximate the total set of significant impacts well enough without increasing too much the number of analysis categories. We therefore present the six domains that in our view are the most involved in the developments of the green hydrogen industry and can cover the majority of its impacts:

- *Employment and working conditions*
- *Material well-being*
- *Health and safety*
- *Personal rights and security*
- *Democratic participation and civic engagement*
- *Education and skills development*

In order to provide meaningful information for the social assessment of green hydrogen supply chains, adaptations of the classical understanding of the capabilities approach are necessary. For this reason, we specify for each of the domains a set of capabilities - inspired by the concept of secondary capabilities [72,94] - that can constitute and define to a more detailed level the content of the domains and provide the basis for operationalization and data collection.

The identification of suitable empirical indicators to account for these capabilities can represent the final level of operationalisation of this framework, although this is beyond the scope of this paper. In assessing social impacts with this framework we can also make a possible distinction between a) protection from capabilities restrictions - i.e. avoidance of damages, compliance with basic rights and satisfaction of basic needs - and b) enhancement of neglected or underdeveloped capabilities by actively creating positive effects with the interventions and satisfying higher hierarchy needs, i.e. expanding possibilities of self-realisation [65]. In section 4.4 we mentioned the results of some empirical research on the factors influencing subjective well-being. These studies support the idea that it is possible to divide needs into the two categories of 'maintenance' and 'growth'. We intend to use these findings to develop our assessment framework. In particular, some capabilities domain - *Employment and working conditions, Material well-being, Health and safety, Personal rights and* security - can be assigned to the 'maintenance' dimension, i.e. they can affect the very possibility of life (meaning a decent life and not just the organism's survival) and therefore should never be negatively impacted. On the other hand, capabilities domains such as *Democratic participation and civic engagement* and *Education and skills development* can be assigned to the "growth" category, since the impact on these capabilities does not call into question the possibility of life itself, but they can determine important aspects of social life quality. We believe that useful information about which conditions are most likely to characterise positive or negative social impacts can be gained by incorporating this additional dimension of hierarchy into the assessment framework. An overview of the impact domains constitutive of the framework, the relative articulation in terms of capabilities and the associated rights of the Universal Declaration of Human Rights and of the EU Charter of Fundamental Rights is presented in Table 1.

**Table 1**
Impact domains, capabilities and associated human rights references related to green hydrogen supply chains.

| Dimension | Impact domain | Green hydrogen capabilities |
|---|---|---|
| **Maintenance** | **Employment and working conditions** | 1. Being remunerated with a **fair wage** [Art. 23.3 UDHR; art. 31 EUCFR]<br>2. Working in **just and favourable conditions** (including fair hours and avoiding precarity) [art. 29, art. 30, art. 31, art. 34 EUCFR]<br>3. Working in compliance with **worker's rights** (including health, safety, freedom of association in trade unions) [Art. 23.1; 23.4; Art. 24 UDHR; art. 28, art. 31 EUCFR]<br>4. Being free from discrimination, **forced labour or exploitation** (including child labour) [Art. 4, Art. 26 UDHR; Art. 5, art. 15, art. 24, art. 31, art. 32 EUCFR] |
| | **Material well-being** | 1. Enjoying an adequate access to **basic resources** (water, nutrition, clothing, housing, medical care) [Art. 25 UDHR;]<br>2. **Energy affordability** [Art. 25 UDHR, Art. 38 EUCFR] |
| | **Health and safety** | 1. Preventing premature deaths from accidents, disease, pollution, deprivation associated with green hydrogen supply chain [Art. 3 UDHR; Art. 2 EUCFR]<br>2. Attaining a good **standard of physical and mental health** [Art. 25 UDHR; Art. 3 EUCFR]<br>3. Accessing **healthcare and information** about health [Art. 25 UDHR; Art. 35, 36 EUCFR]<br>3. Enjoying an **healthy environment** [Art. 37 EUCFR] |
| | **Personal Rights and security** | 1. Being **treated fairly before the law** [Artt. 6–11 UDHR; artt. 20–26, art. 47 EUCFR]<br>2. Living in **secure conditions,** without fear of harassment, degrading treatment or armed conflicts [Art. 4, 5, 9 UDHR; art. 2, art. 3, art. 4 EUCFR]<br>3. Avoiding arbitrary deprivation of **property rights** [Art. 17 UDRH; Art. 17 EUCFR] |
| **Growth** | **Democratic participation and civic engagement** | 1. Participating in **democratic and fair decision making processes**, locally and nationally [Art. 21 UDHR; art. 11, 12, 20, 41 EUCFR]<br>2. Having access to **information** regarding the formulation of policies and projects affecting one's life and environment [Art. 27 UDHR; art. 42 EUCFR]<br>3. Having the possibility to **form and join civic organisations** to engage in decisions affecting them [Art. 19, 20, 27 UDHR; art. 11, art 12 EUCFR] |
| | **Education and skills development** | 1. **Developing the skills** necessary for participating in the labour market [Art. 26 UDHR; Art. 15 EUCFR]<br>2. **Accessing information** and technology necessary to **participate in green hydrogen economy** [Art. 26, 27 UDHR] |

### 5.1. *Employment and working conditions*

The labour dimension represents one of the main social contexts in which the social impacts of green hydrogen can be evaluated. This domain initially concerns the assessment of the capabilities to work in a dignified manner, with the realisation of guarantees and rights not only at the formal level. When considered in the context of green hydrogen, these capabilities address the necessity of ensuring equal opportunities, fair compensation, and just working conditions for all individuals involved in the green hydrogen labour market and economy, including those engaged in the production, distribution, and utilisation of green hydrogen and its upstream inputs. The extraction of raw materials, the construction and operation of green electricity production and electrolysis plants all require labour in different economic, social and legal contexts.

#### 5.1.1. Being remunerated with a fair wage [87,89]

The remuneration of workers within the supply chain is a matter of great importance, with salaries that are unfairly low or otherwise unsuitable for a comfortable standard of living being a significant concern. In fact, lower-paying jobs in renewable energy also present a challenge to a just transition [95]. Furthermore, green hydrogen plants can impact the economic activities and employment dynamics of the areas concerned; for instance, they can be an opportunity for job creation. However, some case studies suggest that the jobs offered are short-term and unskilled or, conversely, require skills that are not available in the local workforce [59,96].

#### 5.1.2. Working in just and favourable conditions [89]

Some scholars also highlighted the lack of research regarding the work quality - in terms of rights and precarity - associated with the transition to low-carbon technologies, especially at the extremes of the value chains and in the logistics stages (Davidson, 2023). Rather than improving labour rights and transforming work, current industry practices may conceivably worsen existing precarity and inequalities for some groups, both in the Global South and North, missing the chance to unlock the emancipatory potential of the socio-technical transition (Davidson, 2023).

#### 5.1.3. Working in compliance with worker's rights [87,89]

The emergence of new value chains will impact a diverse array of workers across numerous occupational sectors. To guarantee a smooth and inclusive transition, the universality of rights and protection must be upheld to ensure the delivery of equitable growth and decent work [95,97]. Those employed in the renewables sector, including those in solar and wind energy, are not infrequently confronted with precarious working conditions and a dearth of robust union representation, paralleling the experiences of other capital-intensive sectors [53,98].

#### 5.1.4. Being free from discrimination, forced labour or exploitation [87,89]

Without particular attention to social issues, green hydrogen deployment can, paradoxically, contribute to the growth of discrimination and inequality [98,99]. Therefore, this assessment evaluates the absence of gender, racial, religious, or other forms of discrimination, as well as the absence of forced and child labour within the supply chain context. It is necessary to ensure that the raw materials needed to expand the renewable installed capacity (e.g. copper, cadmium, indium, nickel, silver, etc.) are not extracted in contexts where work exploitation or child labour is involved, which has to be deemed alarmingly plausible [100]. Despite the harsh and dangerous nature of this type of work, children working in hazardous conditions in mines and quarries are estimated by the International Labour Organization to be several millions [101].

In essence, the capabilities included in the “Employment and working conditions” domain indicate that all individuals should have equal access to acceptable employment opportunities, be protected by the law and be treated fairly in all processes related to employment. These capabilities are enhanced only if the supply chain drives society towards the creation of accessible new skilled jobs, reducing unemployment and distributing economic growth [31]. Conversely, poorly-managed energy transitions can have an overall negative impact on the labour market, possibly creating unemployment in competing sectors without compensating the workforce displacement with adequate policies. The capabilities within this domain resonate with the distributional principle of EJ in its focus on equitable distributional outcomes within the labour market. In this area, it is also very important to assess the procedural side of justice, as fair rules and procedures are the foundation of any lawful and fair labour market. Furthermore, the aspect of acknowledging labour rights, as expressed above, is an indispensable feature for the fulfilment of the dimension of recognitional justice.

### 5.2. Material well-being

This impact domain entails the fundamental rights referring to decent life standards.

#### 5.2.1. Enjoying adequate access to basic resources [87,89]

This capability refers to affordable access to fundamental resources such as drinking water, water for domestic use (e.g. for cooking, washing, laundry, etc.), nutritious food, adequate shelter, clothing and energy services. The hydrogen supply chain requires freshwater at several stages, both indirectly, as in the case of raw material extraction and refining, and directly for the electrolysis process. The rationale for this capability is to underline the need for any green hydrogen project not to engage in water-grabbing practices [102] and not to interfere with the supply of fresh water to people, either in the areas adjacent to the electrolysers or along the different hubs of the upstream renewable energy supply chain, both in Global North and Global South countries [48,103]. To a lesser extent, photovoltaic and wind power generation require a certain amount of water in the early stages of the life cycle and small amounts in the operational phase [104]. However, this may be relevant in areas with reduced freshwater availability, which could be the case for a number of green hydrogen potential suppliers. In addition, the sea, rivers and lakes are an integral part of economic activities such as aquaculture and fishing, as well as agriculture through irrigation. The same applies to land-grabbing practices, since there may be competition for land use between hydrogen value chain facilities and activities such as agriculture, livestock, tourism and biodiversity conservation. In fact, solar and wind farms, necessary for the production of green hydrogen, can be associated with extensive land use due to the installation of wind turbines or solar panels and the associated supply infrastructure (roads, power lines and stations, etc.). Regarding land use, the construction of wind farms or photovoltaic installations can compete with agro-forestry activities [105–107]. However, when compared with the production of bioenergy and biofuel, the impact on soil, biodiversity, land use and water appropriation and quality, renewable hydrogen provides large advantages thanks to the intrinsic higher land use efficiency of PV and wind installations.

#### 5.2.2. Energy affordability [87,89]

This capability refers to the satisfaction of energy needs, specifically access to affordable energy in both exporting and importing countries. In general, depending on the particular configurations of incentives and market dynamics, the deployment of green hydrogen could result in beneficial or detrimental effects on energy prices in both exporting and importing countries. For example, hydrogen penetration may lead to a better satisfaction of energy needs due to the possibility of storing renewable energy from local plants, thus contributing to the alleviation of energy poverty. Conversely, there is a possibility that green hydrogen will prove to be a highly cost-intensive energy carrier, resulting in a significant escalation in energy costs and potentially giving rise to negative socio-economic impacts. Furthermore, in countries that export green hydrogen, demand for electricity from electrolysis plants may compete with domestic demand, potentially leading to internal supply shortages and price increases and it may compete with the decarbonisation of domestic electricity production [33]. It is worth noting that studies regarding low carbon transitions generally find only a modest increase in employment levels, accompanied by a negative distributional effect associated with higher electricity prices [108].

Looking at the distributional dimension of energy justice for these capabilities means that we need to consider the specific distribution of the above-mentioned benefits and harms of green hydrogen initiatives among different stakeholders. The recognition dimension of energy justice is also embedded in this element of the framework, namely the recognition of the right to access basic resources as a consequence of the recognition of the right to life and dignity of the individual.

### 5.3. Health and safety

This domain concerns the possibility of maintaining overall health and safety. Depending on the specific configuration of hydrogen-related projects, this domain of capabilities may be constrained directly, e.g. if working conditions are detrimental to health, or even indirectly if any health-related factor in a given context is negatively affected by green hydrogen projects (e.g. deforestation).

#### 5.3.1. Preventing premature deaths from accidents, disease, pollution, deprivation [87,89]

In essence, this means avoiding exogenous causes of premature death associated with the green hydrogen supply chain. These capabilities also address the safety concerns related to the different stages of hydrogen supply chains (production, storage, and transportation), one of them being the exposure of workers and communities to hazards such as leaks or explosions, statistically linked to failures of pipes, valves or filters in the hydrogen system [109].

#### 5.3.2. Attaining a good standard of physical and mental health [87,89]

Assessing the impact on this capability means evaluating how different processes in the supply chain may impact on people's health. In addition to the production of electrolysis and storage facilities, the industry also encompasses renewable energy generation, raw material extraction, and the manufacturing of machinery. For example, noise pollution [110,111] and shadow flickering [112,113] caused by wind farms has been studied; both can be addressed by taking appropriate measures when designing the system and, in more modern plants, noise emissions are significantly reduced within a radius of a few hundred metres [110,112]. Some studies on the impacts of wind energy take into consideration aspects such as noise and landscape impact [112,114,115]. However, these aspects do not seem to have a perceived consistent impact and appear to be related to the characteristics of the local landscape, the wealth of the local community and whether or not the project provides benefits to the local community [14].

#### 5.3.3. Accessing healthcare and information about health [87,89]

This capability is associated with securing access to essential healthcare, medicines, health services and information necessary to attain a good standard of both physical and mental health. It is of particular importance that individuals are provided with access to information regarding potential health risks associated with supply chain processes. In the event that future research identifies new risks, it is essential that this information is made available to the public so that they may take the necessary precautions. The availability of treatment or preventive measures should be addressed in a similar manner.

#### 5.3.4. Enjoying a healthy environment [89]

On this matter, this domain encompasses the capability to enjoy a healthy environment and to preserve ecosystem services. If green hydrogen is used to decarbonise hard-to-abate industrial plants (e.g. replacing coal in steel mills), we can expect positive effects on the air quality in the surroundings of the previously CO2-emitting (or other air pollutants such as CO, particulate matter, SO2, etc.) facilities. In addition, a growing demand for rare earths in the manufacture of photovoltaic panels and wind turbines, and it is expected that increasing demand for renewable energy will lead to increased mining with the associated impacts [116]. As mining sites expand, they may overlap with protected natural or wilderness areas - or extend to the seabed - posing a threat to biodiversity and wilderness conservation [117]. In general, the decarbonization to which green hydrogen projects aspire can lead to multiple health benefits, for instance by improving air quality and reducing toxic exposures or contributing to mitigate in the long term the multiple health-issues exacerbated by a warmer climate. The distributive justice perspective here is evaluable by looking at the effective final shaping and distribution of health-related benefits and harms of the processes. Regarding the procedural tenet of EJ, local communities affected by the hydrogen supply chain should be enabled to obtain all necessary information on potential risks to human health and safety stemming from the construction and operation of energy facilities and final use of hydrogen.

### 5.4. Personal rights and security

This domain refers to the possibility to live in secure conditions in just and lawful societies. Raw materials and energy sources are often at the centre of geopolitical tensions and armed conflicts involving state actors or armed groups. It is also important noting that the agenda of large energy corporations envisages expanding their market implementing transnational low-carbon infrastructures that, lead only by the logic of profit maximisation, end up causing severely adverse social consequences such as unfair labour conditions, land and water grabbing, "soft" militarization of the territories, public corruption and privatisation of the benefits, in what some authors defined "*green colonialism*" or "'*green' infrastructural harm*" [6,62,63]. It is necessary to evaluate the potential impact of green hydrogen-related infrastructure on existing injustices and security threats in each specific context. This evaluation should determine whether such infrastructure can exacerbate these issues or, conversely, whether it can serve to mitigate them, for instance when decentralised distribution of energy production is realised.

#### 5.4.1. Being treated fairly before the law [87,89]

In evaluating projects and processes pertaining to the hydrogen supply chain, it is essential to consider the extent to which individuals are able to be treated equitably by institutions and the legal framework. In particular, those who are vulnerable must have the means to access the legal system and exercise their rights in pursuit of social and environmental justice. A number of cases have brought to light potential concerns regarding the fairness and equity of law enforcement in contexts across the globe, including in the Global North and South [118–120].

#### 5.4.2. Living in secure conditions, without fear of harassment, degrading treatment or armed conflicts [87,89]

This capability is useful for assessing the impact of conflicts, particularly those that are violent and armed, which may be fuelled by the expansion of the hydrogen supply chain. These phenomena may be the result of actions by state or parastate actors against local communities [121,122], or they may take the form of interstate conflicts [6,58,123].

#### 5.4.3. Avoiding arbitrary deprivation of property rights [87,89]

In this context, the capability of people to safeguard their assets, which are essential for sustaining a decent standard of living, such as land, housing and other resources, is a key consideration. Indeed, the large-scale expansion of renewable energy production areas, mining for raw materials and the construction of necessary infrastructure could potentially give rise to expropriation processes. Some activities along the hydrogen chain demand land use at different degrees. This requires that the property rights of local communities are secured, in particular against forced and extra-legal expropriation, and that legal expropriation takes place with appropriate forms of participation and compensation. Especially in the Global South, there may be a lack of transparency in land lease or sale contracts and a lack of community involvement in decisions, often leading to unfair outcomes and patterns of land grabbing [58,59,114,119,121]. This issue explicitly addresses the procedural pillar of energy justice, but involves also the recognitional justice dimension in demanding the acknowledgement of a political subjectivity and rights to all interested parties.

### 5.5. Democratic participation and civic engagement

Protecting and strengthening the democratic participation of local communities is essential for ensuring the overall social justice profile of green hydrogen supply chains. This domain represents the capability of individuals and groups to be recognised as legitimate participants in the political process and to actively exercise their political rights. It also highlights the importance of involvement and engagement in the decision-making processes that affect one's life. Political agency and recognition require inclusive political systems that ensure the representation of diverse perspectives. The principle of recognition requires addressing inequalities in political recognition and access to participation and representation, rejecting discrimination based on factors such as gender, religion, disability, sexual orientation, ethnicity and possibly others.

#### 5.5.1. Participating in democratic and fair decision making processes [87,89]

This capability requires ensuring that no renewable energy or electrolysis facilities are installed without due process and disclosure of information. Local communities of the various possible geographical contexts need to be recognised as stakeholders and engaged through consultation in the decision-making processes associated with these projects. The right to freely disagree with political decisions without being marginalised or harmed is also fundamental to secure effective participation in the political decisions that govern one's life.

#### 5.5.2. Having access to information regarding the formulation of policies and projects affecting one's life and environment [87,89]

Information pertaining to green hydrogen, associated projects and their supply chains must be accessible and transparent. Moreover, those interested in the potential implications of green hydrogen supply chains must be adequately informed about the risks, opportunities, advantages and disadvantages involved.

#### 5.5.3. Having the possibility to form and join civic organisations to engage in decisions affecting them [87,89]

The potential for all those involved to organise themselves into groups and organisations with the objective of representing their demands and ensuring that their voices are better represented. Some case studies have identified critical issues related to these aspects [114,119].

Here, the main claim of the EJ is clearly on the pillar of recognition as political actors, but it is combined with the procedural aspects that allow actors to participate effectively in the issues that concern them most. Moreover, financial stability and enhanced bargaining power (when appropriately protected) deriving from the employment in the new strategic sector can potentially boost political participation and civic engagement, leading to a more inclusive and representative political landscape.

### 5.6. Education and skills development

The relationship between education and green hydrogen supply chains is not as close or direct as for the basic capabilities previously presented. The domain of education and skills development assesses the extent to which two capabilities can be enhanced: the development of a skills set aligned with the requirements of the labour market and the advancement of technical knowledge and technologies along the green hydrogen supply chain.

#### 5.6.1. Developing the skills necessary for participating in the labour market [87,89]

The implementation of targeted training programmes and the establishment of shared international guidelines on this energy transition can facilitate the development of the requisite skills among vulnerable groups, thereby enabling their participation in this emerging economic sector. The impact on vulnerable groups can be significant, as the availability of green hydrogen jobs has the potential, if managed in accordance with social justice principles, to provide stable employment pathways, thereby reducing poverty and enhancing social mobility. This economic inclusion factor can have a positive effect on participation in social and political life more generally.

#### 5.6.2. Accessing information and technology necessary to participate in the green hydrogen economy [87]

The development of hydrogen supply chains necessitates the advancement of sophisticated and costly technologies involving both the private and public sector level. This can be advantageous when transferring technical knowledge and technologies to the various societal contexts involved. Conversely, the transition may exacerbate existing inequalities if the previous assets and the newly-created economic and social benefits are appropriated by a few. In this regard, the architecture of energy projects and infrastructures becomes once again a matter of distributional justice, recognition of education rights and protection of socially fair procedures.

## 6. Conclusions

The article employed a theoretical approach integrating energy justice, the capability approach and fundamental human rights to develop a framework for the evaluation of the potential social impacts of hydrogen deployment. The framework offers policymakers and stakeholders a comprehensive picture of the social dimensions potentially impacted by green hydrogen energy deployment, including impacts on employment and labour markets, on material well-being, health, justice, democratic participation, and on socio-economic inequality in general. Further, an adaptation of this framework would be suitable to be deployed in future evaluations of the social impacts of deploying other energy technologies, both in academic and policy settings.

The decision to establish the framework on human rights is driven by the objective of implementing it across diverse hydrogen supply chains, both local and global. At the same time, this aspect may prove to be a limitation of this work. Indeed, this extensive generality may result in the failure to capture certain social impacts within diverse socio-economic contexts. The lack of established green hydrogen production precludes the use of case studies and empirical data to determine the most significant dimensions of social impacts. Consequently, the framework will be validated and refined with the further advancement of the research work.

Before the actual application of the framework, it is necessary to distinguish two different approaches for assessing social impacts, namely an ex-ante and an ex-post approach.

The ex-ante approach proves particularly useful at the present time, when the development of green hydrogen systems is still in its infancy, most projects are still at the design or implementation stage (i.e., not yet operational), and supply chains are not well established and developed yet. The different political and economic actors do not share a unified perspective on the future trajectory of these supply chains. In particular, there are ongoing debates concerning production methods, potential applications, and imports [124]. However, there are indications that policymakers and industry are forming bilateral agreements to develop technologies along certain specific paths [125]. In this case, the suggested methodology to anticipate social impacts is based on the combination of secondary data, qualitative and quantitative scenario building techniques. The construction of scenarios describing plausible alternative futures is useful to anticipate challenges and take into account the influence of various factors in shaping the path between the current situation and the possible future configurations [126]. This approach allows us to envision how green hydrogen supply chains might evolve and to determine to which socio-technical contexts our evaluation framework should be adapted. Once the plausible scenarios have been constructed, the framework can guide researchers or policymakers in identifying the impact domains and the plausible affected capabilities within each scenario, thus enabling various prospective accounts of potential social impacts.

For the ex-post approach, the first step concerns the mapping of the specific green hydrogen project (being it a single plant or a hydrogen valley, for instance) to be examined and defining its boundaries. Then, the various impacted domains must be individuated and, within these, the set of capabilities that can actually be impacted must be carefully identified through a context-specific research. Once the socially relevant capabilities have been identified, it is necessary to determine the methodologies that can be employed for the operational assessment of the impact of green hydrogen supply chains on these capabilities. Qualitative research techniques, such as interviews, focus groups and participatory methodologies, are particularly useful for studying complex phenomena in which human interactions play a crucial role. The strength of qualitative approaches is to provide insights into the dynamics of social impact that had not been previously considered and that other more formalised methods are not equipped to capture. Some of these techniques have already been successfully applied in research on renewable energy sources [122,127–129]. Although this approach does not allow a generalisation of results, it can provide context-specific results while pointing to recurring dynamics and wider patterns to pay attention to. Quantitative research techniques, surveys and secondary data analysis can be employed to obtain indicators and/or identify correlations and causal relationships among social variables. This, in turn, enables the application of statistical methods, facilitates the generalisation of results to a larger population and allows quantified comparative studies. Among the quantitative methodologies that can be considered and incorporated into the framework, we mention the Social Life Cycle Assessment methodology [130] for product system reconstruction and assessment of social impacts throughout the life cycle of green hydrogen technologies.

It is our conviction that no method alone is sufficient to convey the complexity of the renewable hydrogen socio-technical system and assess its potential social impacts and the implementation of a triangulation approach will prove useful in facilitating a more comprehensive evaluation. Therefore, the synergetic application of the aforementioned quantitative and qualitative methodologies, in conjunction with case studies and scenario-building techniques, should be employed and integrated in the framework implementation. This framework facilitates the formulation of policies and initiatives based on robust theoretical foundations, thereby ensuring that decisions are not solely driven by economic considerations but also take into account their social sustainability. It can also promote community engagement by recognising the importance of including local voices and concerns in the planning process, thus helping to design projects and/or policies that are more likely to promote inclusive economic growth, reduce undesirable impacts and ultimately be accepted by communities. Energy policymaking is becoming an increasingly complex endeavour due to the far-reaching consequences of the policies designed in areas that stretch well beyond those covered in economic and environmental analyses. Therefore, we advocate for including social impact assessment in all the energy policy design processes. In doing so, drawing on literature on needs, capabilities, well-being, and human rights is a suitable way to embrace both empirical evidence and cultures of human and legal rights, which could complement each other and gain recognition in both academic and policy contexts.

## CRediT authorship contribution statement

**Jacopo Bindi:** Writing – review & editing, Writing – original draft, Conceptualization. **Francesco Bartolomei:** Writing – review & editing, Writing – original draft, Conceptualization. **Giuseppe Pellegrini-Masini:** Writing – review & editing, Supervision, Conceptualization. **Alessandro Agostini:** Writing – review & editing, Supervision, Funding acquisition. **Dario Padovan:** Writing – review & editing, Supervision.

## Declaration of competing interest

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

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## Data availability

No data was used for the research described in the article.

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