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The geography of sustainability transition and materiality: grid-tied solar photovoltaic technology in Sri Lanka

Nanthini Nagarajah

ABSTRACT

The geography of sustainability transition (GeoST) literature views solar photovoltaic (PV) as an off-the-shelf, footloose, absolute technology for bringing about a technological shift in locations with high solar irradiation. Herein, I argue against viewing solar technology in these ways, highlighting that consideration should also be given to the configuration of solar PV that suits the contextual conditions. To this end, I offer empirical evidence for the need to approach solar PV diffusion through a relational perspective. Accordingly, different solar PV technology formats may become necessary for its successful implementation in diverse contexts. Supportive empirical evidence comes from Sri Lanka's large-scale grid-tied solar PV implementation. I conclude the paper with an analytical consideration of the influence of material factors as being as important within GeoST as that of intangible factors, and that technological shift should be pursued within a location's contextual relational materiality.

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1. INTRODUCTION

Solar photovoltaic (PV) is considered a promising technology for countries in energy transition, offering substantial potential and a least-cost option for sustainable energy transition to electricity generation. Fundamentally, the sustainability transition of energy systems refers to the technological shift from fossil fuel-based technologies to renewable energy-based ones, making energy technology and technology development central to this transition. The geography of sustainability transition (GeoST) literature, looking beyond technological fixes, has paid increasing attention to the broader perspective of socio-technical transitions such as policies, discourses, institutions and actor networks related to restructuring energy consumption and production systems (Köhler et al., 2019; Truffer, 2012; Truffer et al., 2015), while also acknowledging the

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importance of considering context in the transition process (Binz & Truffer, 2017; Coenen et al., 2012).

However, the GeoST literature (e.g., Global Innovation System – GIS) presents solar PV as a generic, off-the-shelf, globally applicable technology (Binz & Truffer, 2017). In doing so it pays less attention to the element of relational conditions of the technology's natural material requirements (e.g., land) and context-related stakeholder rationalities that are necessary for the successful implementation of solar PV. A presumption within transition studies has been that once technologies mature, they can be imported and assembled relatively easily using industrial processes, business models, financial investments and policy transfers within any context (Kirshner et al., 2019).

Acknowledging the importance of considering solar PV and context as key for sustainability transition, the paper examines how materialities affect energy transitions in Sri Lanka from both a theoretical and analytical perspectives by focusing on the implementation of large-scale grid-tied solar technology including a demonstration project (DP) on floating solar PV (FPV).

To understand the influences of materiality in the context of solar PV technology in Sri Lanka, a middle-income country, this paper explores the following questions: (1) How does the GeoST literature deal with materiality? (2) How has relational materiality influenced and affected the application of solar PV in Sri Lanka? (3) How does the case of Sri Lanka add to the GeoST literature? Theoretically the paper contributes to a reorientation of the extant literature to pay heed to materiality when contextualising transitions. In consequence to this enquiry, it offers empirical evidence for the need to approach solar PV diffusion through a relational perspective. It informs that land, the absolute materiality, needed for large scale grid-tied ground-mounted solar PV is a fiercely contested matter and that alternative forms of PV technology needs to be considered to exploit and achieve sustainable energy transition from the country's plentiful sun irradiation.

In presenting empirical evidence as to the need for a relational approach when contextualising technology, this paper begins by discussing the GeoST literature's approach to materiality, followed by the methods section. The empirical section describes the implementation of grid-tied solar PV in Sri Lanka, presenting sequentially the conundrum in scaling-up with ground-mounted solar PV, considering FPV as an alternative, and going for a DP to legitimise the alternative as a solution. The paper finally discusses the case with conclusions.

The case presented in this paper raises awareness of the complex contextual characteristics and adverse materiality factors impacting the scaling up of large-scale grid-tied ground-mounted solar PV. The case also highlights that the alternate solution is better legitimised by means of a DP.

2. THE GEOGRAPHY OF SUSTAINABILITY TRANSITION AND MATERIALITY

2.1. Role of materiality in GeoST

In conceptualising transitions, major structural changes have been referred to as socio-technical transitions rather than only technological transitions (Markard et al., 2012), as they are based on a contextual understanding of the technology (Grin et al., 2010). In the electricity sector, sustainability transition centres on implementing emerging sustainable energy alternatives, while phasing out unsustainable technologies and revisiting policies, practices and ways of organising (Markard, 2018). Thus, sustainability is concerned with innovation-based change to energy generation and consumption.

The GeoST literature, a broader field, highlights the need to explicitly focus on embedding territorial particularities of the contexts in which a transition occurs (Coenen et al., 2012; Truffer & Coenen, 2012). It also signals the need to attend to the global interconnectedness of processes (Mura et al., 2021; Truffer et al., 2015, 2022; Wieczorek et al., 2015) and innovative practices associated with transitions (Binz & Truffer, 2017; Coenen et al., 2012; Hansen & Coenen, 2015). Thus, the primary focus of GeoST has been on 'understanding how and why transitions are similar or different across locations' by evaluating the influence of place-based factors such as institutional settings, local cultures, social networks and infrastructure or resource endowments on transitions to sustainability (Köhler et al., 2019, p. 14). GeoST is also about understanding how transitions 'travel' between and/or across different scales, such as related innovations, knowledge and technologies 'beyond where they were initially conceived' (Köhler et al., 2019, p. 14). GeoST (energy) further deals with the distribution of different energy-related activities across a particular geographical space and the connections and interactions between it and other spaces (Bridge et al., 2013). Transitions are thus context dependent, take different directions and unfold at different speeds with interconnected underlying processes (Markard, 2018). A local transition process is therefore impacted by its place-specific context, greatly influencing and contributing to geographical transition unevenness (Coenen et al., 2012).

Despite this, transition studies place technology and technology development at their centre. Technology development involves linkages between heterogeneous elements (Grin et al., 2010), typically attending to the broader perspectives of socio-technical transitions that encompass institutional structures, lifestyles and infrastructure 'beyond a mere diffusion of specific technological fixes' (Truffer, 2012, p. 182). The GeoST literature is populated by discussions of intangibles (Köhler et al., 2019) such as the roles of discourse and institutions in transition policies (Kern, 2011), the involvement of multiple actors (Bekirsky et al., 2022), the roles of power, politics and how policies shape transitions (Geels, 2014; Hess, 2014; Normann, 2017), changes in user practices, and the governance and management of transition towards sustainability (Kemp et al., 1998; Rotmans et al., 2001). It also looks at the need to support novel technologies, business models, organisations and infrastructure (Markard, 2018). The engagement with context-related debate and materiality (i.e., contextualising technology) within the GeoST literature is limited and appears to have been taken for granted, given the fact that (1) the global sustainability transition concept primarily refers to a sustainable technological shift; and (2) this technology change is greatly influenced by its place-specific social and natural material requirements.

2.2. Technology as an end-product of transition

GeoST considers sustainability transition-related (energy) technologies as an electricity sector end product and considers the above-mentioned socio-technical dimensions to play crucial roles in shaping such implementation. For example, the GIS (e.g., Binz & Truffer, 2017) literature analyses technological innovation processes in transnational contexts using generic GIS configurations. For instance, authors consider solar PV as a footloose GIS categorised under 'standardised valuation', leading to it becoming a standard product with 'relatively undifferentiated preferences' by end users globally, or a product supplied 'without much need for adaptation' to specific contexts (Binz & Truffer, 2017, p. 1289). This technology generalisation fails to recognise that what is considered a sustainable practice or solution in one place may not be so in another (Fontaine, 2020). Technology in the GeoST literature has thus far been presented generically, especially as solar PV becomes 'extremely affordable at grid-scale and is being installed rapidly in many countries' (Sareen & Kale, 2018, p. 270). This reflects a lack of nuance or discussion about why certain designs or infrastructure based on the same technology category (e.g., solar PV) are preferred over others in different contexts.

2.3. Contextualising technology

Freeman (2001, p. 156) stated that 'technologies cannot be taken "off the shelf" and simply put into use anywhere', to which Hansen and Coenen (2015, p. 95) added that 'sustainability transitions are geographical processes – they are not pervasive, but happen in particular places, i.e., actual geographical locations with a materiality to them'. Different contexts provide different potentials and challenges, which influence innovation and technology progress (Jakobsen et al., 2019). Similarly, McCann and Soete (2020, p. 17) stated that 'the challenges faced by different contexts differ, and therefore actions need to be tailored to the local context'. This is also true of technology. Within different contexts, even footloose technology hardware must be changed to navigate social and environmental factors differing from those for which it was perfected (Gandenberger & Strauch, 2018). In the absence of such modifications, newly imported energy technologies will likely face tensions, contestation, negotiation and/or rejection for context-specific reasons. Thus, technology should be defined relationally as 'technologies-in-context' (Rammert, 1997, p. 176) by also attending to its physical aspects. Similarly, from an innovation perspective, Fløysand and Jakobsen (2011) highlighted that innovation practice should be viewed as relational. These authors focus on the actor network, knowledge flow, related assets and network interconnectivity that allow for a relational view of the innovation practice.

The geographical locations of many low- and middle-income countries offer them strong potential for generating solar energy (Energy Sector Management Assistance Program, 2020; World Bank, 2020). Yet their contextual challenges restrain them from rapidly harnessing this energy source using the footloose technology described in the GIS literature (Calvert et al., 2022; Yenneti et al., 2016). Those in countries suggesting that the use of end-product solar PV technology is unproblematic overlook the fact that natural materiality (e.g., land, rooftops) for such implementation is finite and may lead to new controversies and resistance to these technologies (Fontaine, 2020). Large-scale land use for solar PV can invoke local socio-culture barriers (Konadu et al., 2015). For example, the population of a large proportion of low- and middle-income countries depends on agriculture; thus, the installation of large-scale ground-mounted solar PV creates competition and raises livelihood and social issues (Sanseverino et al., 2021; Stock, 2022; Taye et al., 2020) in addition to material barriers to technology deployment. Silva and Sareen (2021) have shed light on this issue through a study of people's perceptions of ground-mounted solar PV infrastructures and their effects on the local community.

2.4. Relational materiality

The availability of renewable natural resources such as solar irradiation may be restricted to within a physical territory (e.g., open space) and renewable energy generation can be socially and politically impacted by actor networks across different scales (De Laurentis & Eames, 2016). While the general motive of key stakeholders is to produce sustainable electricity, different actors have varying – and often contested – rationalities regarding technology development. The complex phenomenon requires an understanding of the motives, practices, conflicting interests, tensions and negotiations. In the discussion on urban materiality, Rutherford (2014) stated that contestation of change processes and practices is a result of the diverse ways in which people understand and engage with materials and the influences of materials on their living spaces. The motive of some stakeholders for adopting ground-mounted solar PV is mainly economic. For instance, according to Ockwell et al. (2008), technology transfers for sustainability transitions from technologically developed countries to those countries dependent on the import of technology lead to commercialisation, financially benefitting the involved companies. In contrast, the very low-income local inhabitants who have ground-mounted solar installed in their vicinity experience disruption to their lives and livelihoods (Stock, 2022). Within GeoST, this local-level relational materiality cannot be considered in isolation or taken for granted.

Within the literature, sustainability narratives are not always consistent with observed realities (Fløysand et al., 2017). Thus, technology not being solely an end-product, energy transition technology also affects particular settings and subsumes varying material and immaterial relations (Figure 1).

Thus, the GeoST literature has been passive regarding the implications of energy transition on social relations to land and surrounding environments (Calvert et al., 2019; Hansen & Coenen, 2015) and has taken relational materiality for granted, that is, it views technology as

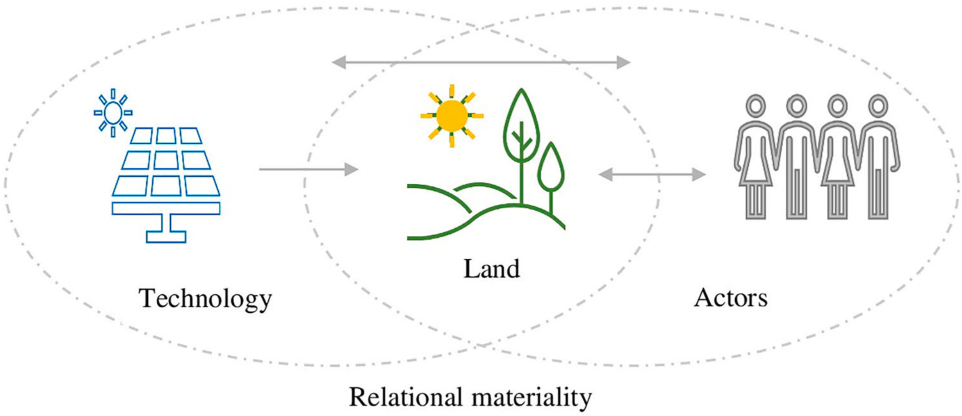

Figure 1. Relational materiality: interactions among technology, the natural environment and actors.

the absolute solution. I argue herein that it is important to attend to this relational materiality when contextualising technology, for example, in the development and application of large-scale solar PV infrastructure.

3. METHODS

This study is part of the Capacity Building and Establishment of Research Consortium (CBERC) collaborative project between Norway and Sri Lanka. The project, established in 2017, aims to strengthen university research collaboration and industrial partnership on clean energy technologies between both countries. CBERC is comprised of Norwegian and Sri Lankan researchers and industrialists. The project includes research on identifying influencing factors on the process of applying renewable energy technologies in Sri Lanka.

This study employed a qualitative case study approach to provide in-depth contextual enquiry on a real-world phenomenon (Yin, 2009). Empirical evidence emanating from collected data is used in this paper to illustrate the role of materiality in energy transition. The data relate to large-scale grid-tied solar technology implementation in Sri Lanka. The data collection comprised 50 semi-structured interviews, participant observations and document reviews. The interviews were carried out in four phases with individuals connected with the Sri Lankan electricity sector, including the public sector, private sector, academics and energy experts. Additional data were collected by participant observation in sustainable energy generation-related conferences and the launch of the FPV DP held in Sri Lanka as well as reviewing energy sector-related Sri Lankan documents. Interviewees were initially identified by attending a Sri Lankan conference on renewable energy and later snowball sampling was practised to find more interviewees. In-depth semi-structured interviews were carried out with stakeholders in Sri Lanka and Norway. In Phase I, in Sri Lanka, 30 face-to-face interviews were carried out between November 2019 and February 2020. This was with stakeholders engaged in renewable energy technology implementation in Sri Lanka, which included representatives from public and private sectors, academics and energy experts. While in Sri Lanka, the author attended the launch of the country's first FPV DP (Kjeldstad et al., 2022) as well as a related stakeholder conference. The DP was part of the CBERC project. Phase II interviews with 11 Norwegian stakeholders from the private sector and academia connected with Sri Lanka's renewable energy programme were carried out digitally on Zoom from August 2020 to March 2021 due to the COVID-19 pandemic lockdown. The interview questions in Phases I and II were not specific to the implementation of grid-tied solar technology, instead captured diverse themes on the transition to renewable energy technologies in Sri Lanka. Phase III involved eight digital group interviews carried out in May 2021; and Phase IV involved one face-to-face interview in Norway in September 2022. The questions in Phases III and IV were exclusively focused on Sri Lanka's solar and FPV DP implementation.

I also studied a number of secondary sources, with a summary provided in Table 1. Interviews were audio-recorded, transcribed verbatim and analysed manually together with documents and participant observation. The interviews were mainly conducted in English, but some of the interviewees preferred to respond in their mother tongue (Tamil or Sinhala).[1] The data production and protection complied with the Norwegian Centre for Research Data's ethics of informed consent and safe storage of data. The categories and data related to absolute materiality were primarily drawn from documents, while those relating to relational materiality were mainly taken from both interviews and participant observation. The entire research process was iterative between audio-recordings, interview transcripts, documents and notes from participant observation, and the recategorisation of the data.

4. IMPLEMENTATION OF LARGE-SCALE GRID-TIED SOLAR PV IN SRI LANKA

Electricity generation from solar PV is expected to become the most abundant, lowest cost and most relevant energy source in the mid-to-long term (Breyer et al., 2017). This has led to a

Table 1. Summary of data used for the analysis of grid-tied solar implementation in Sri Lanka.

Phase	Data type	Timeframe	Details
I	Primary	November 2019–February 2020	• Participation in stakeholder conferences • Participation in the launch of the floating solar photovoltaic demonstration project • 30 face-to-face interviews (Sri Lanka)
II		August 2020–March 2021	• 11 digital interviews (Norway)
III		May 2021	• Eight digital group interviews (Norway and Sri Lanka)
IV		September 2022	• One face-to-face interview (Norway)
	Secondary		• Central Bank of Sri Lanka: annual reports • Ceylon Electricity Board (CEB): Long-term generation expansion plan and annual reports • Sri Lanka Sustainable Energy Authority: reports and website • Asian Development Bank (ADB) and World Bank: reports and websites • Newspaper feature articles • Pre-feasibility report • Letter from the local authority • General reports, newspaper articles and websites

growing number of reports across the GeoST literature about successful solar PV-driven energy transitions in different contexts. For example, studies have highlighted the use of solar PV technology as a substitute system in coal-powered regions of the European Union where utility-scale installations on abundantly available land increasingly attract institutional investors and electricity companies (Bódis et al., 2019). Countries such as Australia identify solar PV as an effective technology for decarbonising their cities (Newton & Newman, 2013). Solar PV has also been regarded as an ideal technology for countries near the equatorial belt because of their stable solar energy irradiation (Kabir et al., 2018). These countries are therefore expected to drive the global expansion of solar PV capacity and the market for solar PV, thereby contributing to local and global reductions in CO_2 emissions (Dobrotkova et al., 2018; Shahsavari & Akbari, 2018). Countries in this geographical belt are largely categorised as developing (Foroudastan & Dees, 2006) and many of them face impacting contextual factors due to the need for rapid renewable energy implementation as mentioned above.

4.1. Absolute materiality

Sri Lanka, a tropical island on the equatorial belt with substantial solar energy resources most of the year and an average temperature of 28°C in dry areas, is ideal for solar PV (Gunaratne, 1994). According to the National Renewable Energy Laboratory (NREL) (Renné et al., 2003), the country has an annual average global horizontal irradiation range of 4.5–6.0 kWh/m^2/day, further evidencing its ample solar resources for year-round PV application (Renné et al., 2003; RMA Energy Consultants (RMAEC), 2014) with a potential to deploy approximately 16 GW solar power (Asian Development Bank (ADB) & United Nations Development Programme (UNDP), 2017; Bellini, 2022). Nevertheless, and primarily because of contextual materiality factors, only 0.01% has been generated through solar power by 2016, despite the expectation that 32% of the country's annual electricity demand would be met this way (Ministry of Power & Energy, n.d.; Perera, 2016). With solar PV costs decreasing globally, Sri Lanka's Long Term Generation Expansion Plan (LTGEP) 2022–2041 stipulates the use of solar to reach 2874 MW by 2030 (Ceylon Electricity Board (CEB), 2021). The International Renewable Energy Agency (IRENA) (2022) informs that the country had reached 434 MW of installed solar power by 2021. Exploitable solar energy potential estimates are based mainly on access to land with competing demands, site accessibility and electrical transmission network access (RMAEC, 2014). While the latter two have financial implications, land-related material issues carry more crucial social implications, often involving serious socio-economic and environmental consequences.

4.2. Relational materiality

Added capacity for generic ground-mounted solar PV modules requires considerable land space (Sanseverino et al., 2021). Ground-mounted PV solutions require 1–2 ha of land to generate 1 MW of power (RMAEC, 2014). Sri Lanka, which covers an area of 65,610 km^2 and has a population of 22.1 million people, is regarded as the 19th most densely settled country in the world, with a population density of 353 people/km^2 (Central Bank of Sri Lanka, 2021; Food and Agriculture Organization (FAO), 1999). Thus, land is in high demand, with 40% used for agriculture, 30% covered by forest and wildlife reserves, and the remaining 30% available for all other activities, including urban and infrastructure development (Mapa et al., 2002). Approximately 77.4% of the population resides in rural areas and depends on agricultural for their livelihoods (Department of Census and Statistics, 2021). Four-fifths of the country's poor depend on the rural sector and almost half of the rural population are small-scale farmers (International Fund for Agricultural Development (IFAD), 2019).

In general, rural spaces are sought-after for large-scale infrastructure technology development such as solar because of their exposure to high solar irradiation, but the land space is also contested for diverse economic and livelihood activities. Land is scarce in Sri Lanka because of high population density and high dependence of the population on land spaces for livelihood-dependent agriculture. The country also needs land for income-generating tourist parks and wildlife reserves, and to maintain conservation and reforestation. In view of these factors, competition for land between the above-mentioned requirements and solar development becomes inevitable (Kjeldstad et al., 2022; Sanseverino et al., 2021; Stock, 2022) in countries such as Sri Lanka. Consequently, rural land becomes contested materially and discursively (Calvert et al., 2022; Stock, 2022). The northern, eastern and southern regions of the country, which are reportedly better than the western region for generating solar energy (CEB, 2021), are also where the rural population resides and is tied to land use for farming, shelter, leisure, social and other income-generating activities. Installing panels in their midst means recasting land use and livelihoods, from cultivation, cattle- and sheep-grazing pastures, and integrated farming to the construction of houses and other buildings, felling trees and clearing green spaces. As shade from solar panels is also expected to decrease crop yields, installing large-scale panels on peoples' most productive farmland is unlikely to be in their best interests (University of Massachusetts Amherst, 2022). Scholars have also highlighted that extensive use of land for large solar PV installations will displace other uses and create vulnerabilities (Adeh et al., 2019; Sanseverino et al., 2021; Stock, 2022). A private sector representative stated the following:

> When you say 100 MW, it requires a vast amount of land and that land has to go through the criterion that it is not cultivatable, because once you install it, it is there for 20 years minimum. So that land will not be available for anything else. Normally these lands are not available in the suburban or urban areas [but rather in rural areas]. (Private sector-December 2019)

While the LTGEP commits to increasing renewable energy generation, production through ground-mounted solar PVs has thus far been slow due to high competition for land from population density, prioritising the preservation of rich biodiversity, agricultural needs and reforestation (Kjeldstad et al., 2022; World Bank, 2021). Apportioning land for solar farms amidst demands for diverse land use creates novel social and environmental problems. Installing grid-tied solar technology in close proximity to human settlements also creates uncertainties, and health and environmental concerns. Theiventhran (2021) pointed out that solar farm protests by rural Sri Lankan residents were in part due to health fears of heat emissions from large solar panels. Environmentalists fear that tree loss from these projects, including the palmyrahs, which are native to places with rich renewable resources, will disrupt natural biodiversity (National Wind Watch, 2016). The interviews also reflected rural residents' concerns regarding the ecological effects of infrastructure installations. A public sector representative revealed the following:

> The materials have been brought but the public is protesting. The public is in the mindset that these [solar PV] will affect the environmental cycle and they don't see this as a positive initiative. The other issue is the land. When we try to install it on private land there will be a lot of issues and protests. To do the interconnection, we have to put up new transmission lines. To do that we have to cut down trees, clearances have to be obtained and there will be protests from the public when cutting down trees. (Public sector-December 2019)

Identifying and allocating suitable locations for solar farm project is a materialistic conundrum for Sri Lanka, given its need for swathes of land for nature conservation and tourist parks, as these protected forested and wildlife areas bring this economically constrained country much-needed revenue. Sri Lanka's expansion of ground-mounted solar is thus challenged by demands for too much of its contested land and because different stakeholders relate to the technology differently regarding its effects on social and natural environments.

In 2016, Sri Lanka also introduced a rooftop solar scheme through the Battle for Solar Energy Programme effort to shift to low-carbon energy generation (CEB, 2021; Dutt, 2020). This offered electricity consumers the opportunity to become prosumers, allowing them either to sell excess power to the CEB or to bank it for future use. Fast-tracking rooftop solar is a necessary policy and exercise, yet without tangible incentives such as upfront grants or installation loans, its wide uptake has also been slow in economically constrained Sri Lanka. One interviewee expressed the following:

> Most of our domestic consumers consume less than 60 units [monthly], which is approximately Rupees[2] 300–400. Approximately 4–5% of consumers consume more than 400 units [monthly], and obviously pay a very high bill. For them, going for solar-rooftop maybe worthwhile economically. (Private sector-December 2019)

Interviewees asserted that the rooftop solar initiative became increasingly popular among high-end electricity users who invested in it and were able to eliminate their monthly bill and even sell their surplus. However, this was not an option for most low-end users because of a high upfront investment costs and low power consumption.

4.3. Floating solar PV (FPV) alternative

FPV technology was considered a better option for overcoming the difficulties experienced with grid-tied ground-mounted solar PV in Sri Lanka, and possibly for countries where land is at a premium and electricity grids are weak (World Bank, 2018). The first commercial FPV installation was in California in 2007, with the main purpose of reducing evaporation from irrigation tanks (Sanchez et al., 2021). The technology has since moved from smaller DPs to larger capacity developments in countries such as India, Laos, Thailand, Vietnam, and China (World Bank, 2021). FPVs are preferred for evaporation reduction, avoiding soiling due to dust and augmenting electricity generation through water cooling (Boduch et al., 2022; Fereshtehpour et al., 2021; Rosa-Clot et al., 2017; Sanchez et al., 2021). Engineered as conventional solar panels atop structures such as floats and pontoons anchored in calm waters and connected to onshore electrical connections (Merlet & Thorud, 2020), FPVs complement conventional ground-mounted and rooftop PVs. FPVs may hold great potential for countries with high solar irradiation, ample waterbodies and land contestation. This option is additionally attractive in Sri Lanka as energy experts have identified the availability of large, suitable and diversely distributed natural and man-made waterbodies (*DailyFT*, 2020).

In 2017, Sri Lanka embarked on the idea of FPV initiated by a private Norwegian solar company. In following up on this idea of FPV, the solar company carried out a pre-feasibility study in 2018 (Solheim, 2018). This study was undertaken in Badaragama, a village in the western province, with a view to installing a 50-kW FPV pilot plant. Despite the study and stakeholder consultation, local authorities and residents could not be persuaded to give consent for the project, primarily because the target waterbody (tank) irrigates the village's cultivable land. A large segment of land surrounding the tank is used for human settlement, industry and service activities (Solheim, 2018). Moreover, the tank water is used for paddy, banana and vegetable farming:

> The local farmers did not see the bigger picture of renewable energy as opposed to the local power plants, so they didn't have that scope of thinking, and the local authorities also did not see any big advantage for them. (Private sector-May 2021)

This relational materiality factor halted the project when local (public sector) authorities wrote to express their constituents' concerns about the technology and its effects on biodiversity, the community and their livelihoods. Phase III group interviews disclosed another perspective: that certain segments of society were strongly attached to their place and agrarian way of living and thus sceptical of modernisation:

> Sri Lanka is an agrarian society. Farming, land, and water are three precious things. Anything to do with these needs real convincing (Academic-May 2021).

Ongoing research on FPV examines different aspects of the technology (Boduch et al., 2022), and its social and natural environmental implications. FPV is a globally respected technology, yet the idea and technology were new in Sri Lanka. The offer of placing this new technology on a waterbody heavily exploited by the residents was thus accompanied by concerns, questions and ultimately resistance, despite experts opining that FPV was superior to ground-mounted solar and thus an appropriate solar solution for the country. The stakeholder responses and reactions to the initial FPV idea in 2017 necessitated further research on the suitability of this technology to overcome these relational materiality concerns.

4.4. Legitimisation through FPV DP

Reinforced by the outcome and experience of the initial FPV idea as presented above, a DP was initiated through the CBERC project. The need for an FPV DP was identified and supported by a delegation of Norwegian private companies visiting Sri Lanka in 2018 to explore and study the energy landscape as part of the CBERC project. The placement of a DP was decided in order to demonstrate that FPV is an innovative technology suitable to Sri Lanka's context and to allay stakeholder relational materiality concerns via the following: (1) evaluating technical feasibility; (2) openly displaying the effects and interactions between the technology and natural and built environments; (3) responding directly and with evidence to stakeholder concerns and questions; and (4) developing solar policy through a consultative process.

Consequently, an FPV DP with a 46-kW capacity (in a pond) and a 5-kW stand-alone reference plant (on land) was launched at the University of Jaffna in northern Sri Lanka (Figure 2) in early 2020. The Norwegian energy group Equinor AS in conjunction with Innovation Norway, a state agency promoting innovation and industry development, provided

Figure 2. Floating solar photovoltaic (PV) demonstration plant.
Source: University of Jaffna, Sri Lanka.

financial support to Current Solar AS Norway which designed and implemented the project. Initially, the purpose of the DP was to test, display, learn, improve and convince stakeholders by placing the experimental FPV in Sri Lanka's climate; however, it became an innovative initiative itself.

Despite falling short of a real-world placement, the university premises with its learning ambience was selected to mitigate concerns and scepticism through education and interaction. One academic stated:

> There will be many challenges to having it elsewhere … people will ask many questions. This is why we decided to have the plant at the university … people wanted to first learn about the technology (Academic-May 2021).

The private sector also undertook this initiative to tap local industrial development potential through joint Norway–Sri Lanka ventures. As expressed by one private sector interviewee:

> With Sri Lanka's number of reservoirs and lagoons, it has been estimated that there is huge potential for developing FPV if one only utilised 10–15% of this surface. With such enormous potential, there should be ample opportunity to use clean energy in the future and develop a local industry in the process. The potential is gigantic. (Private sector-January 2021)

The plant currently functions as a floating research lab carrying out multidisciplinary research, including technical, economic, social and environmental studies, to innovate the technology to suit Sri Lanka's context.

> A lot of data is going into the system and the specification is unusual and we have a lot of measuring instruments related to this system that you would not ordinarily find if the purpose were only to produce electricity. (Private sector-May 2021)

Although FPV panels are similar globally, the floating structures are context specific, with their designs and mounting mechanisms dependent on the type of water, flow, waves and wind speed.

> Solar panels need to be mounted and need to float. Calculations are needed, and material and material sizes as well as floating structures have to be developed according to the context. In this DP, we placed the panels in a zigzag design to float. The panels will thus absorb the sunlight in the morning and evening, whereas the ground-mounted ones only receive sunlight from one direction. Our study on this FPV plant has shown that it produces 8% more than the reference plant, which was also the main purpose of the DP. (Academic-September 2022)

The DP encountered difficulties before and after the launch. Based on data collected from technical observations, appropriate DP modifications have been made. For example, FPV is expected to increase the cooling effects, leading to increased output. However, research from this DP showed that, for Sri Lanka's temperature, additional instruments and designs were needed to monitor this cooling effect:

> The pond is small, and the water temperature is equal to the air, so it does not provide a lot of additional cooling. This was a surprise to us. Night-time is hotter in the water than in the air. Another surprise is that in the dry season, it dries out completely. (Private sector-May 2021)

These effects were also a result of the DP covering a small portion of the pond's surface, the rest of which was exposed to the sun. The researchers noted that evaporation can be mitigated by expanding the water body surface coverage. A recent study at this DP showed that the technology performs stably throughout the year (Kjeldstad et al., 2022). To date, the DP is considered successful considering that it has received local media publicity and visits from financial institutions, students and public sector officials; it appears to appeal to policymakers who set national capacity targets, as evidenced by the recently published LTGEP 2022–2041; and exploration of installing FPV within the parliamentary complex is underway (Razeek, 2022). An excerpt from the LTGEP 2022–2041 reads as follows:

> A floating pilot solar power plant with a capacity of 42[46] kW was installed at the University of Jaffna in 2020[,] marking the country's first such project as a pilot project. Moreover, the Sri Lanka Sustainable Energy Authority has identified multiple potential reservoir locations to develop large[-]scale floating solar projects, and detailed techno-economic assessments for each resource site are required for long term investment decisions … . (CEB, 2021, n.p.)

Currently, electricity produced by this DP meets the consumption needs of the University of Jaffna (Kilinochchi). One academic opined that, for Sri Lanka, the model for introducing a renewable technology is as follows: an initial DP, followed by a private project, and finally, scaling up through government projects to ensure suitability and uptake.

5. DISCUSSION

The GeoST literature primarily focuses on 'understanding how and why transitions are similar or different across locations' by evaluating how place-based factors influence institutional settings, local cultures, social networks and particular infrastructure or resource endowments towards transitions to sustainability (Köhler et al., 2019, p. 14), acknowledging the importance of geography (Hansen & Coenen, 2015; Truffer & Coenen, 2012). While conceding that place-based factors influence the pace of transitions across locations, the GeoST literature has not given much attention to technology itself playing an impactful role on geographical transitions. Energy transition primarily concerns a shift from one technological system to another – a material, tangible shift. Yet the GeoST literature has overlooked the need to contextualise technology, or rather has confused technological fixes with absolute materiality by presenting technology as the mere needed end product of a transition process. GeoST needs to acknowledge that materiality plays a crucial part in the application of transition processes and that materiality is context specific. The intent herein has been to explain that inadequate attention has been paid, both theoretically and analytically, to the role of materiality in transitions in geographies.

Theorising transition needs to embrace the idea that innovation and technologies are created in one part of the world and spread to other countries through technology transfer (Köhler et al., 2019). When embedding these technologies in the local contexts, they need to be altered to befit the context and to be used for purpose or rather they too need to be contextualised using local capacities and knowledge, and by also encouraging innovations from within (Ghosh et al., 2021). Therefore, technology in transition cannot be regarded as footloose or off the shelf (Freeman, 2001) but instead needs to be adapted suitably to fit within the social and natural contextual particularities of a target context (Fontaine, 2020; Gandenberger & Strauch, 2018). Analytically, this contextualisation of technology cannot be studied in isolation or in its absolute form but must instead be viewed in relation to its natural material requirements (e.g., land, in the case of ground-mounted solar PV). However, land and technology in their absolute forms must also be viewed in relation to varying stakeholders' rationalities, emphasising the need for the literature to attend to relational materiality (Figure 1) when contextualising technology in GeoST.

This paper began with the illustration of a solar PV system as a footloose technology in the seminal work by Binz and Truffer (2017, p. 1289), where it is placed within a 'standardised valuation', revealing that 'end-users have relatively undifferentiated preferences that are uniform in various parts of the world'. Herein, I argue against this, highlighting that even proven technologies such as PV, which is globally regarded as footloose for generating energy from solar, must be adapted to befit a particular context, that different solar PV technology formats may be necessary to fit different contexts, and that those differing technologies are not footloose but context-affected and require context-relevant changes.

The empirical case of grid-tied solar PV implementation in Sri Lanka was analysed herein. Many actors in Sri Lanka did not view the implementation of footloose, multi-located, large-scale, ground-mounted solar PV as a solution to sustainable energy transition. The gigantic solar potential described by interviewees demands large-scale land use, which may only be plausible in its absolute form, in isolation from a relational perspective. In reality, the island nation is challenged with diverse land use that stretches beyond agricultural livelihoods and includes established allocated lands for forest and wildlife reserves, conservation of rich biodiversity, other land-based economic activities besides urban and infrastructure development. Further making space for large-scale solar power generation in closer proximity to human settlements adds to the conflict between their living space and electricity generation through solar. Such developments largely take place on rural spaces and their peripheries where the lives of people are well intertwined and engaged with the land space. As evidenced by this study all these factors lead to conflicts and resistance and in the end become a barrier to technology development.

Aside from electricity production, such large-scale technology implementation compels a community to choose between survival needs and sustainable energy – or a context in which livelihood, personal and/or local benefits are prioritised and embraced over global-level benefits (Komendantova, 2021). For policymakers, the choice is often a trade-off between large-scale implementation for sustainable energy, and conservation of biodiversity and people's welfare. For foreign private investors, Sri Lanka's geography is ideal for solar energy and technology set-up for profit and growing dividends. The differences in priorities, concerns, choices and actions – drawn out through discursive claims articulated by actors across networks (public, private, academic and energy experts) – empirically confirm that land space is a contested valued materiality in Sri Lanka, and one not easily granted for ground-mounted solar PV. Such differences also show that land (absolute materiality) is tied to varied relationships among stakeholders (relational materiality). These contextual, real-world factors emphasise the need to find alternative PV technology in order to realise its benefits. The empirical evidence herein also highlights that footloose solar PV technology, as it is conceptualised in the literature, is unlikely to be implementable as such in countries such as Sri Lanka.

The case also illustrates that the prevailing relational dimension of materiality in Sri Lanka, presenting as a relative material barrier to ground-mounted solar PV, prompted a rethinking that eventually led energy experts, private sector stakeholders and policymakers to propose FPV as a possible alternative solution for the country and to innovate context-relevant designs, consequently becoming a driving force for local innovation.

The influence of contextual factors on sustainability transition engenders trials, tests and verification by native researchers, and negotiations with stakeholders and users. The contextual factors also encourage stakeholders to alter and uncover alternatives while offering opportunities for developing, improving on and using local capabilities for innovations. The initial plan for a pilot FPV plant resulted in rejection because concerns raised by the local authority and the community that was heavily reliant on the waterbody were insufficiently addressed by the relevant stakeholders and because it was believed that FPV would affect marine biodiversity. In other words, the fact that relational materiality was not given due consideration by the actor networks contributed to the initiative being discontinued.

In light of this empirical evidence and experience, the initiative to bring together Norwegian and Sri Lankan academics and private sector stakeholders, to combine local contextual knowledge with global technological expertise to demonstrate to the native stakeholders and users of the suitability of FPV through a DP confirms the usefulness of collaborative work. By being responsive to the contextual particularities and attending to the interrelatedness between the indigenous energy sources, landscape, infrastructure and human–environment relationships, the DP has led to a tailored innovative process as revealed by short-term assessment. DP is an absolute materiality. How different actors, nature and the immediate environmental characteristics connect and relate to this materiality is what determines whether the project will prompt acceptance of the new technology to achieve low-carbon solutions. In this case, while the main purpose of the FPV DP was to display, learn and shape the technology to befit the context and produce sustainable electricity without placing greater competition on already-contested land space, there have also been other consequential benefits. These have included, as mentioned by the interviewees, academics exploring improved electricity production efficiency (Kjeldstad et al., 2022) in their own context, the private industries incentivised as a result of legitimisation of adapted technology, policymakers securing a legitimised alternative solar option for large-scale expansion (CEB, 2021), contested rural landscapes avoiding further demand for land space, and a local university engaging in sustainable energy generation in its own context through research, national and international collaborations, and networking (University of Jaffna & Western Norway University of Applied Sciences, 2022).

It is also true that while the DP herein was not a purely real-world setting for observations or soliciting feedback and perspectives of residents living nearby, it does illustrate the expectations of different stakeholders. Importantly, the case shows that absolute materiality (technology, land, water) is not isolated from the relational dimension, and that renewable energy technologies for sustainability transition demands the absorption of contextual relational materiality (rationalities of actors towards the absolute) for an effective and sustainable transition process.

6. CONCLUSIONS

Within the literature, insufficient attention has been paid to materiality, and technology has been taken for granted as an end-product in a transition process. This is despite the contextual heterogeneity within the GeoST. The technological characteristics of the tangible have received scant analytical or theoretical consideration. A presumption within transition studies has been that once technologies mature, they can be imported and assembled relatively easily in other contexts (Kirshner et al., 2019). This presumption is especially the case for solar PV technologies, instigated by the falling prices of PV panels and the fact that their improved performance is considered ubiquitous (Markard, 2018). A few studies have highlighted that the innovative process has resulted in the growth of solar PV by way of revisiting their political, economic and cultural energy landscapes (Kirshner et al., 2019). Nonetheless, scant consideration has been given to relational materiality within the GeoST, that is, how footloose solar PV is influenced by social and natural place-based conditions. Sri Lanka's grid-tied solar energy transition journey leading to requiring the legitimisation of FPV by means of a DP affirms that successful implementation of technologies demands not only legitimisation/acceptance among a broad set of social actors such as policymakers, financial institutions and other key stakeholders (Njøs et al., 2020), but also alignment with the technology's natural material requirements. Failure to acknowledge the contextual relational dimension of technology (e.g., that land for ground-mounted solar energy generation is finite) can create controversies and hamper transitions

(Fontaine, 2020). While rural land-related contestation for any development activity is a global fact, in relative terms, conflicts arising from demands for sizable land such as for ground-mounted solar PV is significantly more acute in population-dense countries such as Sri Lanka, again bringing to the fore the need for a context-sensitive approach to materiality and consideration of alternate forms of solar PV technology.

By engaging with real-world conditions in the realisation of solar PV technology in Sri Lanka, this paper illustrates how important it is to contextualise technology by paying closer attention to the relational dimension. Similarly, by scrutinising the role of relational materiality in contextualising technology, this paper underscores and informs the extant literature that the materiality (tangible) aspect of solar PV technology development is as important as the intangibles widely discussed in the GeoST literature. This study also affirms that establishing and strengthening international collaborations not only enables technology transfers but also encourages domestic innovation, including technological alterations for adaptation, by means of developing and improving domestic capabilities and capacities.

Thus, this paper contributes to the literature by offering empirical evidence of how and why relational materiality influences the uptake of footloose technology. While the GeoST field is broad, this study contributes a single case study. Further research in different geographical contexts will be needed to validate and generalise these case study findings.

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1 Translations from Tamil or Sinhala into English were carried out by the author.
2 Sri Lankan currency.

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