様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Early-Stage Sustainability Assessment of Carbon-Nanotubes-Enabled Renewable Energy Technologies using Ex-Ante LCA and Sound Material-Cycle Index

研究課題名（英文）Early-Stage Sustainability Assessment of Carbon-Nanotubes-Enabled Renewable Energy Technologies using Ex-Ante LCA and Sound Material-Cycle Index

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交付決定額（研究期間全体）：（直接経費）　　3,400,000円

研究成果の概要（和文）：このプロジェクトは、環境の持続可能性に向けたイノベーションのための実験室実験を支援するフレームワークを提案した。LCA評価手法を反復的に適用し、実験の決定が環境に及ぼす潜在的な影響を知らせる。従って、実験者は、環境性能とともに技術的改善を評価することができる。カーボンナノチューブ技術によって可能になった薄膜シリコン太陽電池とリチウム硫黄電池の2つのケーススタディを調査した。これらの技術は、温室効果ガスの排出を削減するだけでなく、（a）予想される太陽電池パネルの廃棄物をアップサイクルする、（b）重要な電池正極材料への依存を減らす、といった幅広い社会的意味合いを持つ。

研究成果の学術的意義や社会的意義
1. Scientific. The project demonstrated a "concurrent technology development and assessment" concept to ensure an innovation is environmentally sustainable.

2. Social. We showed that thin-film Si solar cells and Li-S batteries can give Japanese renewable energy industry a competitive advantage.

研究成果の概要（英文）：This project proposed a framework to support laboratory experiments to innovate towards environmental sustainability. We applied LCA evaluation method in an iterative manner, to inform potential environmental consequences of an experimental decision. Therefore, the experimentalists could evaluate the technological improvements along with the environmental performances. Two case studies were investigated, thin-film silicon solar cells and lithium-sulfur batteries enabled by the carbon nanotubes technology. Apart from mitigating greenhouse gas emissions, these technologies have a broader social implication, (a) upcycling to-be-expected solar panel wastes, (b) reduce dependency on critical battery cathode materials.

The outcomes of the project were presented in several international conferences, invited lectures, conference proceedings etc. Currently, two peer-reviewed papers are under revision; two are in the process of submission.

研究分野：Environmental science

キーワード：lithium-sulfur batteries　thin-film si solar cells　carbon nanotubes　ex-ante LCA　sustainability

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

The global solar panels and lithium-ion battery industries have been dominated by a few developing countries with cheaper production costs and easier access to raw resources. To revitalize Japanese industries, a breakthrough in technologies is needed. One competitive advantage is the development of next-generation renewable energy devices enabled by carbon nanotubes (CNT), which is the material that was first discovered in Japan. These technologies include thin-film c-Si solar cells and lithium-sulfur (Li-S) batteries that are at lab- and pilot-stage, respectively.

To ensure the competitiveness of emerging technologies, not only the technology performance but also the superior sustainability performance must be achieved. Early-stage interventions, such as selecting appropriate materials and improving production processes through laboratory experiments, could prevent environmentally unsustainable outcomes. Therefore, an ideal experiment should be supported by technology assessment tools, including life cycle assessment (LCA).

２．研究の目的

This study aimed to develop a framework to support concurrent technology development (at an experiment lab) and assessment (prospective environmental impact). We worked closely with a university lab to demonstrate the applicability of the concept. We adjusted some of our initial objectives through trial-and-error interdisciplinary collaboration. The final objectives were as follows:

i. To develop a generic ex-ante LCA method for the lab-stage technologies, i.e., solar cells and batteries;
ii. To develop a dynamic material flow analysis (MFA) to show the social implementation of technologies, i.e., the potential to upcycle solar panel waste in Japan;
iii. To develop sustainability assessment indicators to show the socio-economic impact of technologies, i.e., sulfur-based batteries replacing cobalt-based batteries

３．研究の方法

We developed the overall methodologies based on the life cycle sustainability assessment (LCSA) toolbox. We demonstrated the applicability of the proposed methods in two case studies: (a) thin-film c-Si solar cells and (b) lithium-sulfur batteries.

(a) Solar cells.

We first measured the inventory from the experiment lab. We performed the necessary scale-up of the processes to an anticipated production (more efficient energy and solvent usage, etc.; example in Figure 1a). Then, we modeled and compared the life cycle GHG emissions of the thin silicon film and conventional silicon wafer.

We explored the social implications of the technologies from a circular economy viewpoint. We conducted a dynamic MFA to estimate the solar panel wastes and silicon demand based on the installation target of new solar panels for the coming decades in Japan. We analyzed under what technological scenarios a self-sufficient solar panel production could be achieved.

(b) Li-S batteries.

We first collected data from previous experiments to set a benchmark inventory for Li-S batteries. We scaled the lab-scale coin cell to a commercial-scale pouch-cell-based battery pack using a BatPaC design model. We investigated various technological improvement scenarios to quantify the environmental improvements based on experiment decisions.

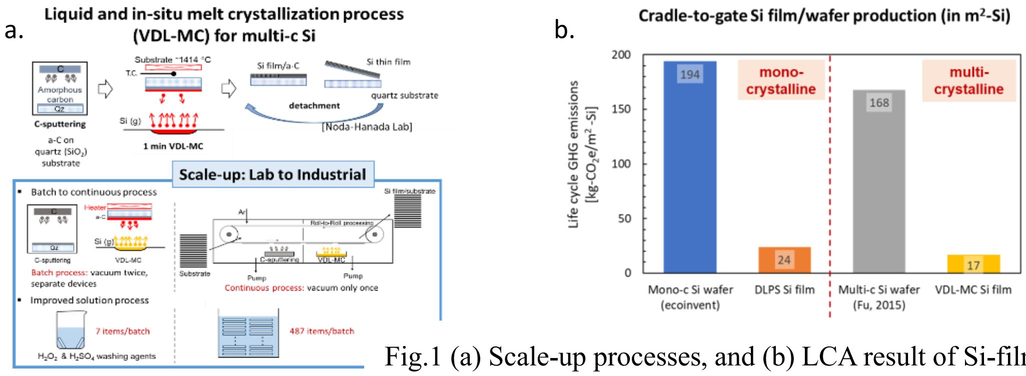

Fig.1 (a) Scale-up processes, and (b) LCA result of Si-films.

４．研究成果

We reported some of the research outcomes at academic conferences, invited talks, proceedings, and peer-reviewed papers. We are preparing more paper submissions while wrapping up the project. Here, we shared the main findings.

(a) Solar cells.

Using thin Si film to replace Si wafer would reduce the silicon amount by 1/10 as the thickness decreases, and kerf losses of silicon sawing were avoided. We modeled the LCA of two processes with different substrates to form the thin Si film, i.e., DLPS and VDL-MS. When compared to the equivalent mono- and multi-crystalline Si wafer, 90% of life cycle GHG emissions could be reduced (Figure 1b). The environmental hotspot was the electricity for vacuuming in rapid vapor deposition. The VDL-MS process has a lower GHG but also probably lower solar efficiency than the DLPS process. Overall, the thin-film c-Si solar cells are more environmentally sustainable if the technology matures.

Figure 2 shows the estimated silicon solar panel waste and installation (production) targets based on the situation in Japan. The former was estimated using a Weibull function model; the latter was estimated using the stated policy targets. We simulated the availability of recycled silicon under two scenarios (optimistic: recycle to solar-grade silicon; pessimistic: recycle to metal-grade silicon). Ideally, Japan can achieve self-reliance and a circular silicon economy if the demand and supply can be matched in the coming decades. We found that only under the optimistic scenario of 2050 could the self-reliance goal be realized (Figure 3). The finding implied that a holistic technological roadmap, including alternative solar cell technologies like perovskite, is needed to revitalize domestic solar panel production.

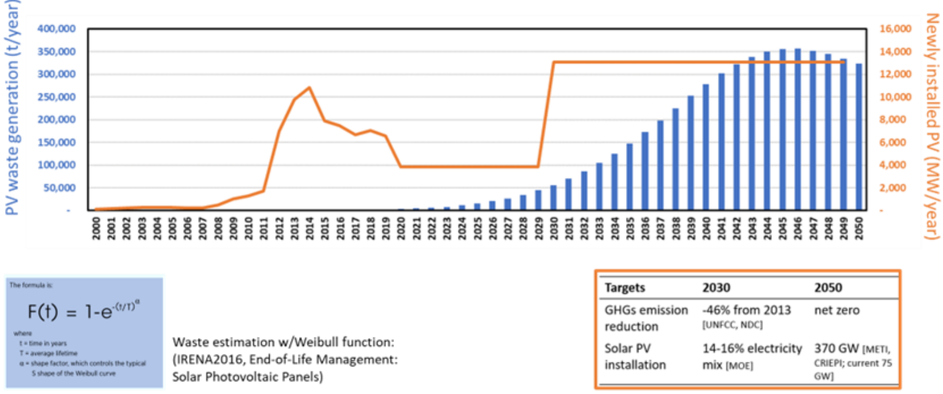

Fig. 2 Projected solar panel waste generation and installation target of new solar panels (production) in Japan towards 2050.

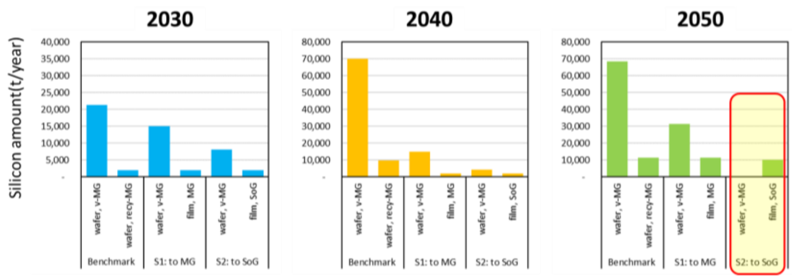

Fig. 3 Scenario analysis results of the balance of silicon demand and supply—only the optimistic technological scenario by 2050 could Japan no longer rely on solar panel imports.

(b) Li-S batteries.

Li-S batteries are regarded as next-generation batteries due to their higher energy density, about 3 to 5 times of current lithium-ion batteries. However, the cycle life is short due to the lithium dendrite and other technical challenges. A potential solution is to use CNT as the sulfur cathode host. Although CNT is an expensive material, both cost and environmental burden, CNT can provide additional functions like substituting as binder, conductive fillers, and current collectors. Therefore, a closer investigation of environmental sustainability is needed.

We leveraged the state-of-the-art knowledge from closed collaboration with battery experts to design some possible technological improvement scenarios. Figure 4 shows the LCA results of producing a 1 kWh equivalent Li-S battery pack. We were able to quantify the environmental impact of technological improvements: reduced aluminum and copper current collectors (S1), reduced lithium metal anode (S2), and reduced solvent during cathode production (S3). The result of 78 kgCO2e/kWh was 20% lower than NMC811, the most advanced lithium-ion battery at the moment, showing promising environmental benefits. We also showed the contribution of each battery component for a better understanding of improvement potential.

Figure 5 shows a detailed comparison of the proposed Li-S process with conventional NMC cathode production. We found that adding a pre-filtration process reduced the energy demand for solvent drying, thus significantly improving environmental performance. Overall, when swapping out critical metals like cobalt from a battery component with new technology, we sometimes enable changes in other components and processes that may have surprising impacts. Technology developers and LCA practitioners need to work closely together.

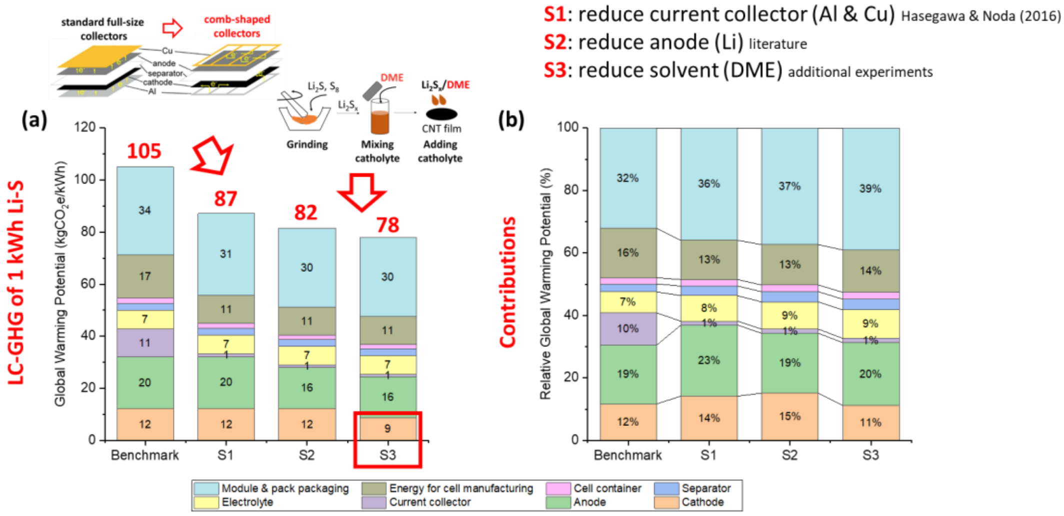

Fig. 4 (a) LCA results of producing a 1 kWh Li-S battery pack in technological improvement scenarios, and (b) the contribution analysis by percentage.

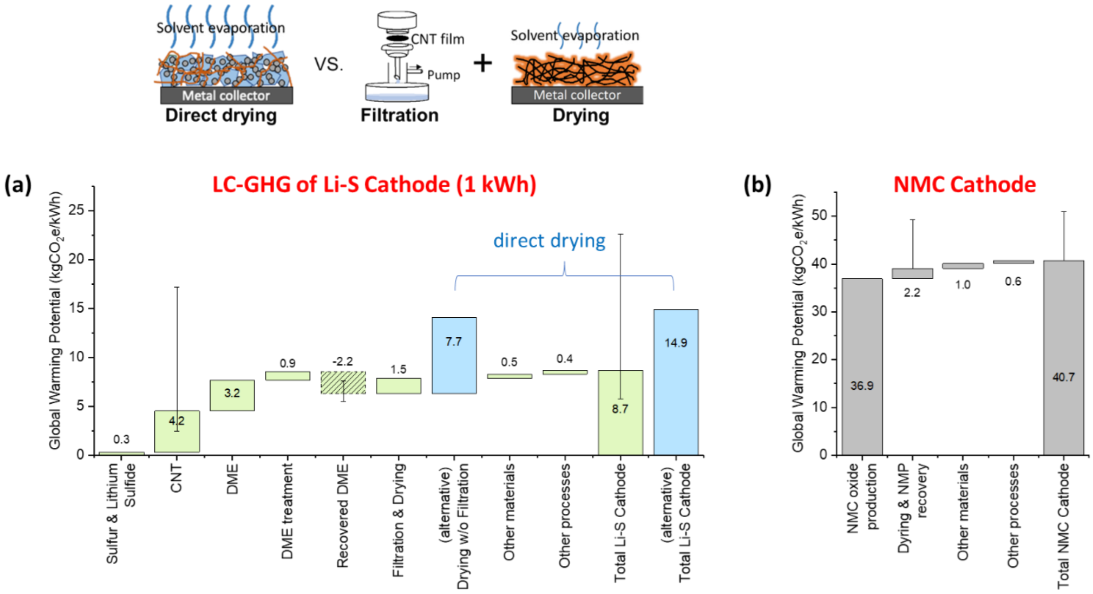

Fig. 5 Detailed LCA results of (a) Li_2S_8-CNT cathode production and (b) conventional NMC cathode production.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　0件）

１．著者名 Asokan Vivek Anand、Teah Heng Yi、Kawazu Erin、Hotta Yasuhiko	４．巻 190
２．論文標題 Ambitious EV policy expedites the e-waste and socio-environmental impacts in India	５．発行年 2023年
３．雑誌名 Resources, Conservation and Recycling	６．最初と最後の頁 106829～106829
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.resconrec.2022.106829	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　4件）

１．発表者名 Qi Zhang, Kotaro Yasui, Suguru Noda, Heng Yi Teah
２．発表標題 Concurrent Technology Development and Life Cycle Assessment of Lithium-Sulfur (Li-S) Battery
３．学会等名 Ecobalance 2022, The 15th Biennial International Conference（国際学会）
４．発表年 2022年

１．発表者名 Heng Yi Teah, Ziyi Han
２．発表標題 Closing the Silicon Loop: A Lifecycle Environmental Implication of Upcycling Japan’s Solar Panel Wastes into Next-Generation Thin-Film Silicon Solar PV Cells
３．学会等名 Ecobalance 2022, The 15th Biennial International Conference（国際学会）
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１．発表者名 Vivek Anand Asokan, Heng Yi Teah, Erin Kawazu, Yasuhiko Hotta
２．発表標題 Ambitious EV Policy Expedites the e-Waste and Socio-Environmental Impacts in India
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４．発表年 2022年

１．発表者名 Minami Suto, Heng Yi Teah, Suguru Noda
２．発表標題 Thin silicon films reduce life cycle GHG emissions of crystalline silicon solar cells
３．学会等名 The 14th Biennial International Conference on EcoBalance（国際学会）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関