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Renewable green oil as a low-cost option for large-scale, long duration energy storage to produce on-demand electricity

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ABSTRACT

The rapid growth of renewable solar and wind energy necessitates extensive, long-term energy storage solutions to stabilize the electric grid and address the intermittent nature of these sources. In the absence of cost-effective long-duration, large-scale (LDLS) energy storage, there is a risk of increased disruptive blackouts and brownouts as intermittent energy sources approach 50% of electricity generation. Our analysis underscores volumetric energy density as a pivotal determinant in LDLS energy storage solutions, which is particularly crucial during periods of diminished renewable resource availability, such as the rainy season. Despite emphasis on conventional electric batteries and mechanical storage technologies such as compressed air and pumped hydro for LDLS, their costs pose a significant obstacle to widespread adoption, especially in emerging economies. In this study, we present a groundbreaking approach to LDLS: on-demand electricity generation from carbon-neutral renewable oil, known as "green oil," leveraging Reliance's innovative catalytic hydrothermal liquefaction (R-CAT-HTL) technology. Our investigation evaluated two distinct sources of green oil production: organic waste streams (e.g., municipal solid waste, agricultural-waste, etc.) and on purpose production of algal biomass. We demonstrate that burning renewable green oil to produce electricity offers a cost-effective solution for large-scale (GWh) long-duration (many days) energy storage, ensuring the stability, reliability, and resiliency of the electric grid. We also demonstrate that minimum 14 days, ideally 30 days energy storage is needed for continuous uninterrupted service, especially critical for manufacturing facilities. Through a meticulous levelized cost of storage (LCOS) analysis comparing green oil with other LDLS technologies reported in literature, we demonstrate the cost effectiveness of green oil. In this model, green oil serves as stored energy, functions akin to a battery and is efficiently converted into electricity through conventional reciprocating engines or next-generation more efficient turbines. Our findings suggest that green oil derived from diverse organic sources is the most economically viable option for GWh-scale storage, particularly when storage requirements extend beyond a single day. This research thus presents a transformative cost-effective solution to the pressing challenge of LDLS energy storage, accelerating a sustainable and resilient energy future.

KEYWORDS

Long duration large-scale energy storage; Levelized cost of electric energy storage; Renewable energy and electric

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Abbreviations

A2O	Algae to oil
Bbl.	Barrel of oil
CAES	Compressed air energy storage
Capex	Capital expenditure
CF	Capacity factor
DOD	Depth of discharge
ETP	Effluent treatment plant
H2	Hydrogen
HHV	Higher heating value
LCOS	Levelized cost of storage.
LDLS	Long duration large scale
LHV	Lower heating value
Li- ion	Lithium- ion
MBES	Moving block energy storage
MSW	Municipal solid waste
NH3	Ammonia
O & M	Operation and maintenance
OECD	Organization for Economic Co-operation and Development
Opex	Operational expenditure
PHS	Pumped hydro storage
RCAT- HTL	Reliance catalytic hydrothermal liquefaction technology
RTE	Round trip efficiency
STP	Sewage treatment plant
VRF	Vanadium redox flow

1. Introduction

For sustainable living in the 21st century, renewable electricity is critical, and stabilization of electric grids will require a long-duration large scale (LDLS) energy storage. The LDLS need will increase further as we increase the share of intermittent renewable energy sources such as solar and wind. Traditionally, fossil fuels have served as the backbone of electricity systems, offering readily available, high volumetric energy density, and simple storage options. Their robust technologies efficiently provide base load power and facilitate rapid load balancing. Due to their nonrenewable nature, fossil fuels need to be phased out to address impending climate change crisis. Almost every country and industry has set 'Net zero' goals with ambitious renewable energy investments. Renewable energy sources such as solar and wind energy are not uniformly available throughout the day and can exhibit significant seasonal variations to produce and deliver energy continuously 24x7 to the end customers. Hence, there's a crucial requirement for cost-effective energy storage solutions which enable the capture of surplus energy during periods of abundant wind and solar power, ensuring a reservoir of stored energy for stable electricity supply during times of low or no renewable energy availability. Large-scale generation of electric energy by solar PV and advanced windmills is rapidly increasing world-wide. However, overcoming intermittency is largely discussed with small scale and short duration energy storage (the order of hours). This paper demonstrates that long duration large scale (LDLS) energy storage is a critical need, of the order of days or weeks, to address intermittency and seasonal shortfalls to provide reliable 24x7 electricity supply to end customers.

The intermittency challenge can be explained by demonstrating the energy storage requirements of a large-capacity solar PV plant where the solar resource availability varies from month to month, with a significant reduction in electrical output during the rainy season. If we consider 8 hours of average daily constant solar radiation, then considering this, we need at least 16 hours of additional charging capacity for the storage system for 24x7 supply. To achieve this goal, we will need to build at least 3 times greater solar PV plant capacity (8 hrs. directly from the solar PV plant and 16 hrs. from the energy storage system), assuming uniform daily solar radiation throughout the year. Typically, the capacity factor of a solar PV plant is only 20%, so the daytime solar capacity is typically five times greater than the total capacity, and in principle, an equivalent storage capacity is needed. However, even then, this simplistic approach is insufficient for accommodating the seasonal variations such as rainy season, as illustrated later. Our rigorous analysis demonstrates minimum long-duration large-scale (LDLS) energy storage requirement for continuous 24x7, 365 days reliable energy supply.

Let's consider a 5 Gw solar PV plant with a 20% capacity factor located in the Kutch region of India, which receives abundant sunlight. Figure 1 shows the monthly output, derived from daily averages, of this solar PV plant, from global solar radiation data[I]. Considering a 20% capacity factor, the output of this plant should be 24 GWh daily and 720 GWh (30 days)/744 GWh (31 days) monthly. The orange line indicates the 720 GWh output, or the average demand for which this Solar PV plant was built. From Figure 1, one can see there is a significant shortfall during the rainy season, from June through September.

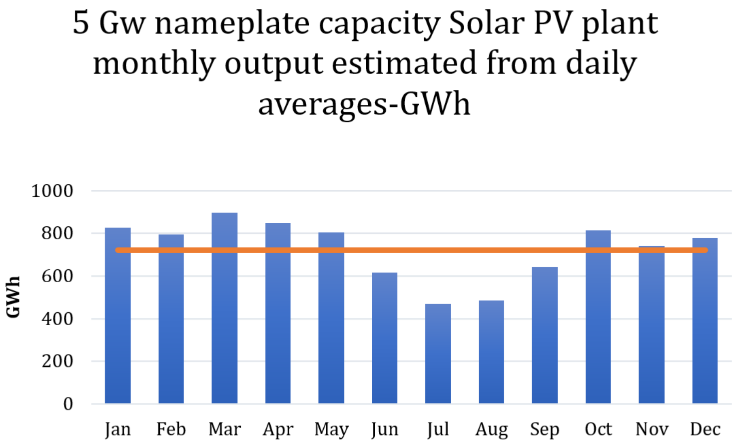


Figure 1. Solar PV plant (5 GW) monthly output-GWh.

The daily average output from each hour from this solar PV plant is summarized for each month in Table 1. The last column is each hour starting from midnight. For the expected 24 GWh output, the total shortfall and excess power are also summarized in Table 1.

Table 1. Energy storage requirements for seasonal shortfalls.

5 Gw solar pv plant													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Hrs.
	0	0	0	0	0	0	0	0	0	0	0	0	1
	0	0	0	0	0	0	0	0	0	0	0	0	2
	0	0	0	0	0	0	0	0	0	0	0	0	3
	0	0	0	0	0	0	0	0	0	0	0	0	4
	0	0	0	0	0	0	0	0	0	0	0	0	5
	0	0	0	0	0	0	0	0	0	0	0	0	6
	0	0	0.0	0.1	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0	7
	0.3	0.3	0.6	0.9	0.9	0.7	0.5	0.5	0.7	0.9	0.7	0.3	8
	1.6	1.6	1.8	1.9	1.8	1.4	1.0	1.1	1.5	2.0	1.8	1.7	9
	2.6	2.7	2.8	2.8	2.5	2.0	1.5	1.5	2.2	2.8	2.7	2.7	10
	3.3	3.4	3.5	3.4	3.1	2.4	1.8	1.8	2.6	3.4	3.3	3.3	11
	3.8	3.9	3.9	3.8	3.4	2.7	2.0	2.1	2.9	3.7	3.6	3.7	12
	3.9	4.1	4.0	3.9	3.5	2.8	2.1	2.1	3.0	3.8	3.6	3.8	13
	3.7	3.9	3.9	3.7	3.3	2.7	2.0	2.0	2.9	3.5	3.3	3.5	14
	3.3	3.5	3.4	3.2	2.9	2.3	1.7	1.8	2.5	2.9	2.8	3.0	15
	2.5	2.7	2.7	2.5	2.2	1.7	1.3	1.3	1.8	2.1	2.0	2.2	16
	1.5	1.8	1.7	1.6	1.4	1.1	0.8	0.9	1.0	1.1	0.8	1.0	17
	0.2	0.4	0.6	0.6	0.6	0.5	0.4	0.4	0.3	0.1	0.0	0.0	18
	0	0	0	0	0.1	0.1	0.1	0	0	0	0	0	19
	0	0	0	0	0	0	0	0	0	0	0	0	20
	0	0	0	0	0	0	0	0	0	0	0	0	21
	0	0	0	0	0	0	0	0	0	0	0	0	22
	0	0	0	0	0	0	0	0	0	0	0	0	23

	0	0	0	0	0	0	0	0	0	0	0	0	24
Total Daily sum-GWh (A)	26.6	28.3	28.9	28.3	25.9	20.5	15.1	15.6	21.43	26.21	24.69	25.10	
At 20% CF-name plate GWh(B)	24	24	24	24	24	24	24	24	24	24	24	24	
(A-B) GWh	2.65	4.37	4.93	4.32	1.97	-3.41	-8.86	-8.32	-2.57	2.21	0.69	1.10	
No of days in month	31	30	31	30	31	30	31	31	30	31	30	31	
Total Excess-monthly (GWh)	82.2	131.1	152.8	129.6	61.0					68.7	20.7	34.0	680
Total shortfall monthly (GWh)						(-) 102	(-) 275	(-) 258	(-) 77				(-)712
Total Days storage require	30												

Table 1 shows that a total of 712 GWh, or approximately 30 days of energy storage capacity, is required to compensate for seasonal shortfalls, assuming that the same plant output is used to store energy and that the energy storage system is charged with excess power when available. This storage requirement can be reduced by increasing the solar plant capacity, but additional Capex is needed, and plants will produce significantly more excess power during non-monsoon months. Table 2 shows the calculations with 20% increase in capacity to reduce the storage requirement, i.e., the plant capacity is increased to 6 GW instead of 5 GW in the previous case.

Table 2. Energy storage requirements for seasonal shortfalls.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Hrs.
	0	0	0	0	0	0	0	0	0	0	0	0	1
	0	0	0	0	0	0	0	0	0	0	0	0	2
	0	0	0	0	0	0	0	0	0	0	0	0	3
	0	0	0	0	0	0	0	0	0	0	0	0	4
	0	0	0	0	0	0	0	0	0	0	0	0	5
	0	0	0	0	0	0	0	0	0	0	0	0	6
	0	0	0	0.1	0.3	0.3	0.1	0.1	0.1	0.1	0.0	0	7
	0.4	0.4	0.8	1.1	1.1	0.9	0.6	0.6	0.9	1.1	0.8	0.4	8
	1.9	2.0	2.1	2.3	2.1	1.7	1.2	1.3	1.8	2.4	2.2	2.0	9
	3.1	3.2	3.3	3.3	3.0	2.4	1.7	1.9	2.6	3.4	3.3	3.2	10
	4.0	4.1	4.2	4.1	3.7	2.9	2.1	2.2	3.1	4.1	3.9	4.0	11
	4.5	4.7	4.7	4.5	4.1	3.2	2.4	2.5	3.5	4.4	4.3	4.4	12
	4.7	4.9	4.8	4.6	4.2	3.3	2.5	2.6	3.6	4.5	4.3	4.5	13
	4.5	4.7	4.7	4.4	4.0	3.2	2.4	2.4	3.4	4.2	4.0	4.2	14
	3.9	4.1	4.1	3.9	3.5	2.8	2.0	2.1	2.9	3.5	3.3	3.6	15
	3.0	3.3	3.2	3.0	2.7	2.1	1.5	1.6	2.2	2.5	2.4	2.6	16
	1.8	2.1	2.1	1.9	1.7	1.3	1.0	1.1	1.2	1.3	1.0	1.2	17
	0.3	0.5	0.7	0.7	0.7	0.6	0.5	0.5	0.3	0.1	0.0	0.0	18
	0	0	0	0	0.1	0.1	0.1	0	0	0	0	0	19
	0	0	0	0	0	0	0	0	0	0	0	0	20
	0	0	0	0	0	0	0	0	0	0	0	0	21
	0	0	0	0	0	0	0	0	0	0	0	0	22
	0	0	0	0	0	0	0	0	0	0	0	0	23
	0	0	0	0	0	0	0	0	0	0	0	0	24
Total Daily sum-GWh(A)	31.9	34.0	34.7	33.9	31.1	24.7	18.1	18.81	25.72	31.46	29.6	30.1	
Daily Requirement-GWh(B)	24	24	24	24	24	24	24	24	24	24	24	24	
(A-B) GWh	7.98	10.04	10.72	9.98	7.16	0.71	-5.83	-5.19	1.72	7.46	5.63	6.12	
No of days in month	31	30	31	30	31	30	31	31	30	31	30	31	
Total Excess-monthly (GWh)	247	301.3	332.2	299.5	222.	21.3			51.5	231.2	168.9	189.6	2065
Total shortfall monthly (GWh)							(-)180	(-)160					(-)342
Total Days storage require	14												

So now the total storage requirement for seasonal shortfalls is 14 days (with 20% oversized solar plant) but it also generates significantly excess power in non-monsoon months. Even with a 20% increase in capacity, a minimum of 14 days of storage is needed. Based on the above two examples we can say that there is requirement of 14-30 days of storage to compensate for seasonal shortfalls with solar PV, even in a relatively sunny part of the world. Some of these shortfalls could be reduced by integrating solar PV with wind in a hybrid system, but this approach does not change the main premise of this work.

This intermittency is not unique to Kutch, India. Figure 2 shows the 1 GW solar plant monthly output at four locations across the globe (Global Solar Atlas) - California USA, Tokyo Japan, Meuro Germany, and Kutch India. The annual solar plant outputs of California, Tokyo, Meuro, and Kutch are 1787, 1344, 1052, and 1744 GWh, respectively.

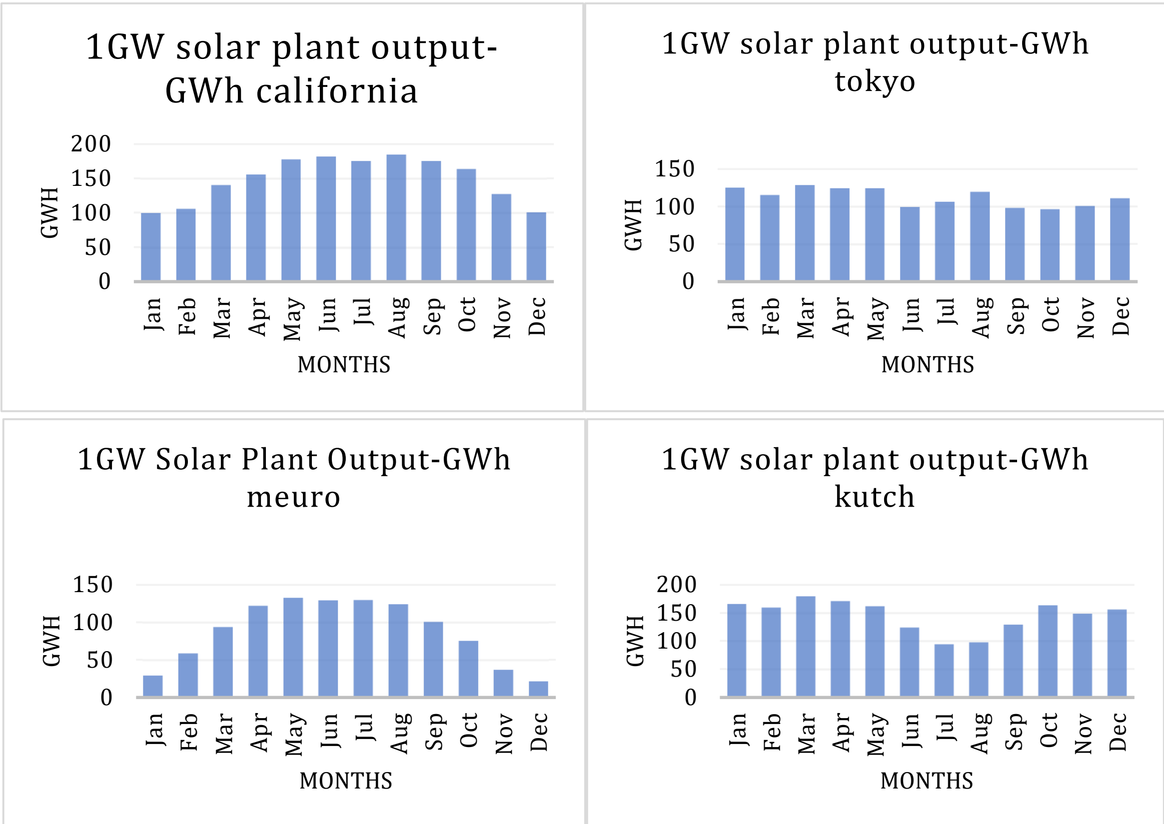


Figure 2. 1 GW of solar plant monthly output at various locations across the globe.

Figure 2 clearly shows that solar PV production significantly varies month to month at all locations, impacting the associated requirements for LDLS energy storage. We believe that at least 14-30 days of energy storage is required for 24x7, 365 days, essentially off-grid, operation. These findings are consistent with views expressed by Bill Gates (2021) and Vaclav Smil (2022) in their books.

Various technologies offer potential for long-duration, large-scale (LDLS) energy storage, such as lithium-ion batteries, vanadium redox flow batteries, green ammonia, green hydrogen, pumped hydro, compressed air energy storage, and moving block energy storage, among others. However, a primary challenge lies in deploying these technologies effectively for LDLS storage lasting days or weeks, as previously mentioned. The high upfront capital cost of investment due to inherently low volumetric energy density coupled with lack of proven track record of such technologies at the required scale is a major challenge. The novelty of this study lies in demonstrating that burning renewable green oil in conventional reciprocating engines (Reciprocating engines are widely used throughout industrial, commercial facilities for power generation) to make on demand electricity, is a cost-effective solution for

Gwh long-duration, large-scale energy storage, by comparing with other options currently being pursued. In this paper, we compare the levelized cost of storage (LCOS) of various energy storage technologies and propose that renewable green oil from Reliance's proprietary hydrothermal liquefaction technology (RCAT-HTL), which has the highest volumetric energy density, can be a reliable, low-cost energy storage option for LDLS.

Using RCAT-HTL, any organic material such as municipal solid waste (MSW), agricultural residues, food and dairy waste, sewage treatment plant sludge, etc., and even on purpose biomass production such as algae can be converted to high volumetric energy density green oil. Compared with thermal HTL, RCAT-HTL uses a catalyst to improve the quality and quantity of green oil. The catalyst also simplifies the overall process by reducing the Capex and Opex. The stored energy in green oil from organic materials is essentially conversion of solar energy through photosynthesis, which consumes CO2; thus, such biogenic green oils are essentially carbon neutral. This green oil can be burned in conventional proven technologies such as turbines or reciprocating engines, to produce electricity. Moreover, green oil can leverage the established storage and transportation infrastructure already in place for conventional fossil fuels, representing a significantly more cost-effective alternative compared to investing in new infrastructure for H2, NH3 or MeOH. This approach of burning green oil represents a simpler way to generate on-demand electricity to balance the changing loads on electric grids to overcome intermittency of renewable power generation. Green oil can be cost effectively transported in large quantities and stored in minimal space for a long period of time, thus providing long-duration large-scale (GWh) energy storage (LDLS) to cater to the days or weeks of energy storage requirement, as identified above. The paper mainly emphasizes the cost comparison of these storage technologies for LDLS- for one day, four days, seven days, fifteen days, and thirty days of storage.

The findings of this study could provide valuable insights into the potential of renewable green oil as a cost-effective and scalable solution for mitigating the challenges posed by intermittency in renewable energy generation. This information could be crucial for policymakers, energy industry stakeholders, and researchers seeking to advance sustainable energy storage solutions and accelerate the transition to a renewable energy future. Our research on renewable green oil as a long-duration, large-scale energy storage solution offers significant benefits to the developing economies with large population and limited capital. Developing countries are already making huge investments in solar PV, wind etc. The following benefits can be realized with our suggested approach:

- Reliable Electricity Supply at lowest cost: Enhances grid stability, reducing the risk of power outages and ensuring a reliable electricity supply to consumers with increasing penetration of intermittent renewable energy sources.
- Environmental Sustainability: Supports the transition to renewable energy by enabling greater integration of solar and wind power, contributing to a cleaner and more sustainable environment.
- Technological Advancement: Stimulates innovation in energy storage technologies, driving progress toward more efficient cost effective and scalable systems.
- Energy Security: Strengthens energy security and independence by reducing reliance on imported fossil fuels and promoting domestic renewable energy sources.
- Overall, this research benefits the target developing country population by improving energy affordability, reliability, sustainability, and security, ultimately leading to a more resilient and sustainable energy infrastructure. The same approach is equally applicable to developed economies as well.

2. Methodology

The primary objective of this research is to demonstrate the potential of renewable green oil for long-duration large scale energy storage and compare the levelized cost of storage of green oil option with that of other established energy storage technologies. The levelized cost of storage of each storage technology is compared with the levelized cost of green oil as energy storage. The methodology includes section 2.1 – brief description of Reliance catalytic hydrothermal liquefaction technology (RCAT-HTL) for green oil production from organic matter Section 2.2 summarizes various levelized cost of storage components for stationary energy storage. Section 2.3. offers comparison of different energy storage technologies (with associated costs). It also includes renewable green oil from municipal solid waste (MSW) and from algae biomass using RCAT-HTL.

2.1. Reliance catalytic hydrothermal liquefaction technology (RCAT-HTL) for renewable green oil production from organic matter

Historically, our energy sources have shifted from low to higher energy densities, the oldest energy source being wood to now fossil crude oil and natural gas with significantly higher energy densities. Table 3 summarizes the energy densities of various energy sources (Engineering Toolbox).

Table 3. Energy densities of different energy sources.

Sr No	Description	Energy Density (MJ/kg)
1	Wood	16-18
2	Charcoal	28-30
3	Coal	30-33
4	Crude oil	42-47
5	Natural Gas	55

The cost of storage and transport, however, is governed by volumetric energy density. In Table 4, the volumetric energy densities of commercial energy sources along with hydrogen are compared (Engineering Toolbox). Hydrogen has the least, while crude oil has the highest, volumetric energy density. The green oil produced from RCAT-HTL technology is similar to fossil crude oil.

Table 4. Volumetric energy density of different energy sources.

Sr No	Description	Volumetric Energy Density (MJ/m3)
1	Hydrogen	10.8-12.8
2	Liquid hydrogen	8,490-10,000
3	Natural gas	36- 40
4	Liquified NG	20,800-23,612
5	Crude oil/ Green oil	36,097-38,513

RCAT-HTL[V] essentially expedites the natural process of crude oil formation in the belly of the earth from ancient biomass deposited millions of years ago, essentially energy from the ancient sun, which we are exploiting today as a nonrenewable resource. RCAT-HTL converts today's biomass or organic material, produced within Earth's current biological cycle, to renewable green oil. Instead of millions of years as taken by nature to create fossil crude oil, RCAT-HTL achieves the process in a few minutes. We are essentially converting the current solar energy captured as biomass or waste organic material (MSW, STP sludge, agricultural residue, etc.) into renewable green oil, which is carbon neutral. In the RCAT-HTL process, biomass is treated under near-critical conditions in the presence of proprietary catalyst and water and converted to green oil and hydro char along with an aqueous purge stream and a minor quantity of gaseous byproducts. Reactions such as hydrolysis, dehydration, condensation, decarboxylation, cyclization, and so forth take place in tandem. For these reactions, water acts as a solvent, reactant, and catalyst, and the added catalyst accelerates these reactions. The catalytic activity of water can be enhanced by using different homogeneous and heterogeneous catalysts. Our proprietary technology enhances the deoxygenation of the produced green oil, increasing both its volumetric and gravimetric energy density. Compared to thermal HTL technologies, RCAT-HTL results in higher yields and significantly higher quality lighter renewable green oil to displace fossil crude oil. This environmentally sustainable process offers a green solution to the global problems of overflowing landfills and waste disposal challenges. The typical costs of green oil production from municipal solid waste are well under 50 $/Bbl. Additional details are given later in the paper. RIL's RCAT-HTL is feed flexible; it can handle both dry and wet biowaste, organic waste, and mixed waste via standalone treatment or co-processing. The green oil from RCAT-HTL can be processed in the existing refining infrastructure to make renewable transportation fuels such as sustainable aviation fuel (SAF), or one could use green oil as an energy storage system or a battery to produce green electricity, which is the focus of this paper.

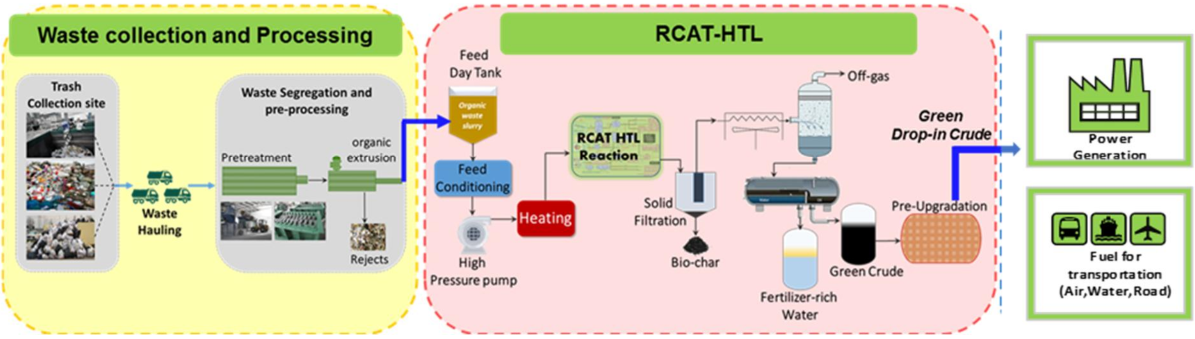


Figure 3. shows the block flow diagram for the RCAT-HTL process and green oil applications.

2.1.1. Features of R-CAT HTL

Feed flexible: Any carbonaceous waste such as food waste, ETP sludge, industrial sludge, agricultural crop residues can be converted to renewable green oil.

No drying: It can handle feedstock containing over 80% water, thereby eliminating the substantial energy expenses associated with drying, a prerequisite step in conventional waste treatment approaches.

Water as the reaction medium: Under RCAT-HTL operating conditions (subcritical conditions), water exhibits a lower dielectric constant, weakens hydrogen bonds, and exhibits a higher isothermal compressibility than ambient liquid water. Water becomes highly reactive, and biomass, breaks down into a liquid renewable green oil.
High-energy recovery: A feed carbon recovery of more than 75% and a feed energy recovery above 85% can be achieved (Sapre, 2022). This is a significant benefit for poor developing countries with limited resources.

As discussed, earlier R-CAT HTL process can handle various feedstocks, including distillery spent wash, kitchen food waste, the organic fraction of MSW, palm oil mill waste, seaweeds, agro-residues, algae slurry, bio sludge, etc. In this paper, green oil production from Municipal solid waste (MSW) is used to generate electricity to demonstrate it as LDLS energy storage. In the case of MSW, the feed HHV varies from 21-25 MJ/kg, and the green oil HHV is 34-40 MJ/kg (Sapre, 2022).

2.1.2. Organic waste availability across the globe

A large amount of waste is generated annually worldwide. Figure 4 shows the per capita waste generated per year (2016 estimated average) and the 2050 projection of waste generation across the globe (World Bank, 2019). Global waste is expected to increase to 3.5 billion tons by 2050. The total quantity of waste generated in low-income countries is expected to increase by more than three times by 2050, with increasing prosperity and population growth.

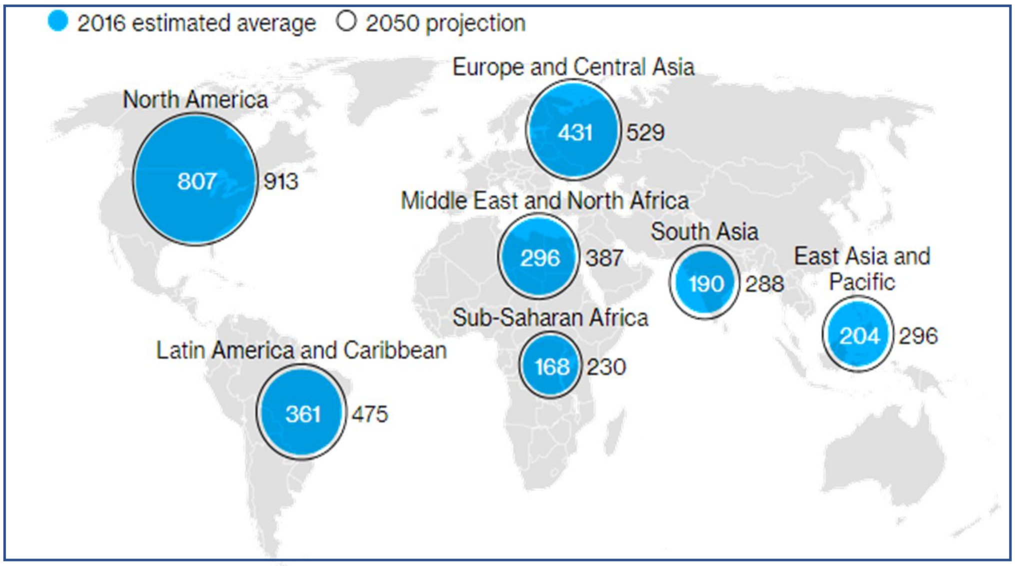


Figure 4. Waste generated across the globe (kilogram per capita) 2016 and 2050 projections.

Table 5 shows that the total available organic waste (Kaza et al., 2018) is ~ 5 billion tons, which includes MSW, food waste, agricultural residues, various organic sludges, etc. (broken down in millions of tons of different types of organic waste streams across globe per annum), and it has the potential to generate green oil and green electricity.

Table 5. Availability of different organic waste products across the globe annually (million tons).

Waste	million tons (per annum)	
MSW	2,240	Potential to generate 4-5 billion barrels green oil per annum (Equivalent to generate 3-4 million GWh electricity)
Food waste	1,200	
Agri Residue	1,000	
STP Sludge	750	

If all this available waste is converted into green oil, there is potential to generate 3-4 million GWh of stored electricity as LDLS to support the green energy transition.

2.2. Levelized cost of storage energy storage.

2.2.1. Key characteristics/Performance metrics of the energy storage systems (Viswanathan et al., 2022)

The key characteristics and performance metrics of energy storage are as follows:

- Rated power capacity: The rated power capacity is the total possible instantaneous discharge capability (in kilowatts [kW] or megawatts [MW]) of the storage system.
- Energy capacity: Energy capacity is the maximum amount of stored energy (in kilowatt-hours [kWh] or megawatt-hours [MWh]).
- Storage duration: The storage duration refers to the amount of time storage can discharge at its power capacity before depleting its energy capacity. For example, a battery with a 1 MW of power capacity and 6 MWh of usable energy capacity will have a storage duration of six hours.
- Cycle life: Cycle life is the amount of time or number of cycles a battery storage system can provide regular charging and discharging before failure or significant degradation.
- Calendar life (years): Defined as the maximum life of the system, regardless of the operating conditions or

the time for which the battery can be stored as inactive or of minimal use.

- Round-trip efficiency: Round-trip efficiency is measured as the percentage of electricity put into storage that is later retrieved or the ratio of the energy charged to the battery to the energy discharged from the battery. It can represent the overall efficiency of the battery system, including losses.

2.2.2. Energy storage system cost components

These costs include both installed costs and O&M costs.

- Storage block ($/kilowatt-hour [kWh]): This block includes the cost of the most basic elements in an energy storage system (e.g., for lithium-ion batteries, this block includes the battery module, rack, and battery management system).
- Balance of system ($/kWh): Includes supporting cost components for the storage block (e.g., for lithium-ion storage, it includes container, cabling, switchgear and heating, ventilation, and air conditioning (HVAC)).
- Power equipment ($/kW): This component includes power equipment for batteries, such as bidirectional invertors, DC-DC converters, isolation protection devices, alternating current (AC) breakers, relays, communication interfaces, and software. The powerhouse for pumped hydro storage and the power island/powering for compressed air energy storage.
- Controls & communication ($/kW): This includes the energy management system for operation of the entire energy storage system.
- Engineering, procurement, and construction ($/kWh): This includes nonrecurring engineering costs and construction equipment as well as shipping, siting and installation, and commissioning of the energy storage system costs.
- Project development ($/kW): This includes costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.
- O&M ($/kW-year): This includes all the costs necessary to keep the storage system operational throughout the duration of its economic life.

LCOS for one day, four days, seven days, fifteen days, and thirty days of storage considered to compensate for the seasonal variation discussed before, and daily intermittency and unplanned outages to ensure smooth and reliable power generation throughout the year. Today's expectation of reliability of electric systems in OECD countries is 99.9999%. It is assumed that this storage can be utilized to compensate for intermittency, seasonal variations, and any other unforeseen outages. For example, the daily electrical output is 24 GWh, 1 Gw x 24 hrs. For 4 days of storage, 24 × 4 = 96 GWh; for 7 days of storage, 24 × 7 = 168 GWh, so on so forth. The storage capacity calculated, and the related Capex and Opex were added to determine the economics of various LSLD options.

2.3. Different energy storage technologies for comparison (with associated costs)

The different storage technologies considered for comparison include lithium-ion batteries, redox flow batteries, pumped hydro, compressed air, moving blocks, green hydrogen, green ammonia (as a hydrogen carrier), and green oil from MSW and algae through R-CAT HTL. The costs of the different storage technologies considered for the LCOS calculations are summarized below. Basic data for the various energy storage systems are given in Table 6; additional details are provided in Reference (Viswanathan et al., 2022).

Table 6. Energy storage technologies.

Sr No	Description	Unit	Lithium-ion	VRF	PHS	CAES	MBES	Green Hydrogen
1	Total Installed cost	$/kWh	359	356	220.6	50.32	190.1	125.9
2	O & M	$/kW	22	24.7	15.5	9.8	25.9	17.5

3	RTE	%	83	65	80	52	84	31
5	Calendar Life	Years	16	12	60	60	49	30
6	DOD	%	80	80	80	80	80	80

2.3.1. Green ammonia as an energy storage agent for green hydrogen

Green ammonia is essentially an energy carrier for green hydrogen, as it is easier to transport and store. In these calculations, the ammonia production from green hydrogen and storage are estimated to be $642 per ton as the operational input cost. Furthermore, a cracker is included to crack green ammonia to green hydrogen for further utilization in a fuel cell for electricity generation. The capital cost of a cracker is estimated to be 1,000 $/kW, that of a rectifier is estimated to be 130 $/kW, and that of a compressor is estimated to be 39.3 $/kW. Furthermore, the stationary fuel cell cost is estimated to be 1320 $/kW (Viswanathan et al., 2022), the inverter cost is 67 $/kW, the control and communication costs are 1.5 $/kW, and the grid integration cost is 19.8 $/kW, which leads to a total installed cost of 2408 $/kW (Viswanathan et al., 2022) A fixed O&M of 17.5 $/kW and a variable O&M of 0.51 $/MWh are included. The energy storage performance metrics include a round-trip efficiency of 31% and a plant life of 30 years.

2.3.2. Green oil from municipal solid waste (MSW) using R-CAT HTL as energy storage

A key premise of this paper is that renewable, carbon-neutral green oil sourced from diverse origins can serve as a long-duration, large-scale (LDLS) energy storage solution for generating on-demand green electricity, functioning akin to conventional battery systems. The organic content of MSW can be converted to renewable green oil with RIL's proprietary catalytic hydrothermal liquefaction technology (RCAT-HTL). This green oil can be converted to on-demand electricity using reciprocating engines or advanced turbines. Additional details and sensitivity analysis are given in a later section. With the tipping fees available in India ($ 10/ton of MSW), the cost of green oil production from MSW is $ 32/Bbl (Reliance Industries Limited). This cost is basis for performing LCOS calculations to compare with the other energy storage options discussed above, as well as sensitivity analysis with varying tipping fees. In OECD countries, the tipping fees are higher, approximately 50-85 $ per ton of MSW. Based on 50 $ per ton of MSW tipping fees, the cost of green oil production is $ -30/Bbl9. This case is also considered for the use of RCAT-HTL in OECD countries.

A total of 37,000 barrels of stored green oil is required to produce 24 GWh of daily electricity. To produce 37,000 barrels of oil, 58,000 tons of MSW required per day. Such amounts of MSW are available in major cities. Furthermore, green oil produced from smaller plants can be easily aggregated, as the transport and storage costs of green oil are low.

For base case power generation, a reciprocating engine (with combined heat and power) is considered. The installed cost of the reciprocating engine (Capex of 1430 $/kW), with a net electrical efficiency of 42% (U. States Department of Energy, 2015), is considered. In the LCOS calculations, a total plant life of 30 years is considered.

2.3.3. Renewable green oil from algae biomass using R-CAT HTL as energy storage

Considering that overall energy storage requirements with high levels of penetration of intermittent renewables in the electrical system, the overall organic waste from various sources may not be enough to be converted to renewable green oil. All the organic waste is nothing but captured Sun's energy after the supply of our food. Typically, we consume 10 times more energy for our well-being compared to energy in the food we produce. Therefore, we need to produce on purpose biomass from sunlight and CO2 in sea water on marginal lands, which can be accomplished using microalgae. The algal biomass is then converted to green oil via RCAT-HTL technology. Based on the work at Reliance on A2O (algae to oil), we believe that at the commercial scale, the cost of green oil will be reach ~100 $ per barrel with increasing capacity, as discussed later. Therefore, $100 per barrel cost of green oil production from A2O is considered for further calculation. This green oil can be converted to produce electricity using reciprocating engines or advanced turbines, as discussed before. The reciprocating engine is considered for power generation. The total installed cost of the reciprocating engine (Capex of 1430 $/kW net electrical efficiency of 42%) is considered (U. States Department of Energy, 2015). Similarly, in the LCOS calculations, a total plant life of 30 years is considered.

3. Theory/calculations

3.1. Levelized cost of storage.

The levelized cost of energy storage can be described as the total lifetime cost of the investment in an electricity storage technology divided by its delivered electricity. In other words, the cost metric of an LCOS is essentially the entire cost over the useful life of a plant. It includes capital costs and operations and maintenance (O&M) costs. It also considers battery degradation over time. The fuel cost refers to the charging cost of the battery. The levelized cost of the storage formula is as follows (Belderbos et al., 2016):

$$LCOS = \frac{\sum(Capital_t + O\&M_t + Fuel_t) \cdot (1+r)^{-t}}{\Sigma MWh_t \cdot (1+r)^{-t}}$$

Where,

- Capital t = Total Capex in year t
- O&M t = O&M costs in year t
- Fuel t = Charging cost in year t
- MWh t = The amount of electricity discharged in MWh in year t
- $(1+r)^{-t}$ = The discount factor for year t

The energy storage requirement is considered as follows, e.g., the daily electrical output is 24 GWh, 1 Gw x 24 hrs. For 4 days of storage, 24 × 4 = 96 GWh; for 7 days of storage, 24 × 7 = 168 GWh; so, on and so forth. Table 7 summarizes the Capex, Opex and LCOS of the various storage technologies for one day, or 24 GWh, as discussed above. The charging cost is added to the Opex where needed.

Table 7. Capex, Opex and LCOS of various energy storage technologies.

Sr No	Description	Capex	Opex (Including charging cost)	LCOS
	Type of Energy Storage	(MM$)	(MM$)	($/kWh)
1	Ammonia	3,019	2,648	0.35
2	Hydrogen	1921	2545	0.33
3	Li-ion batteries	10,787	1,054	0.30
4	VRF batteries	10,680	792	0.24
5	Green oil: A2O	1430	1288	0.16
6	Pumped hydro storage	6600	311	0.10
7	Moving block energy storage	5705	307	0.09
8	CAES	1,693	466	0.07
9	Green oil: MSW (with 10$ tipping fee)	1430	460	0.06
10	Green oil: MSW (with 50$ tipping fees)	1430	(-)404	-0.04

In the case of ammonia energy storage, there is no separate charging cost since green ammonia at 642 $/ton is considered as input. In the case of algae- and MSW-based green oils, there is no separate charging cost since MSW/algae biomass is converted into green oil, a stored energy that is further used to generate electricity.

As discussed earlier, to compensate for seasonal shortfalls and any other unforeseen circumstances, there is a need for long-duration energy storage in terms of days, weeks, and months, as pointed out by Bill Gates and Vaclav Smil. Now, we will look at the LCOS for 4, 7, 15 and 30 days. Table 8 compares the LCOS for the same technologies as above for multiple days storage requirements based on the daily storage requirement of 24 GWh.

Table 8. LCOS of various energy storage technologies for multiple days.

Type of storage	LCOS($/kWh)				
	1day	4days	7days	15days	30days
Li	0.29	0.86	1.43	2.96	5.80
VRF	0.23	0.76	1.29	2.70	5.30
MBES	0.12	0.27	0.42	0.81	1.54
PHS	0.10	0.14	0.19	0.30	0.52
NH3	0.42	0.43	0.43	0.44	0.45
H2	0.27	0.27	0.28	0.29	0.31
Green oil A2O	0.16	0.16	0.16	0.17	0.17
CAES	0.08	0.09	0.09	0.12	0.17
Green oil R-CAT HTL-MSW	0.06	0.06	0.06	0.06	0.06

4. Results and Discussion

As mentioned above, one-day storage and multiple days energy storage capacities were considered for comparison for different energy storage technologies. Figure 5 shows the comparison for one day of energy storage for 24 GWh. It shows that RCAT-HTL-MSW-derived green oil gives lowest LCOS at 0.06 $/kWh, and with higher tipping fees (OECD countries), it gives negative LCOS.

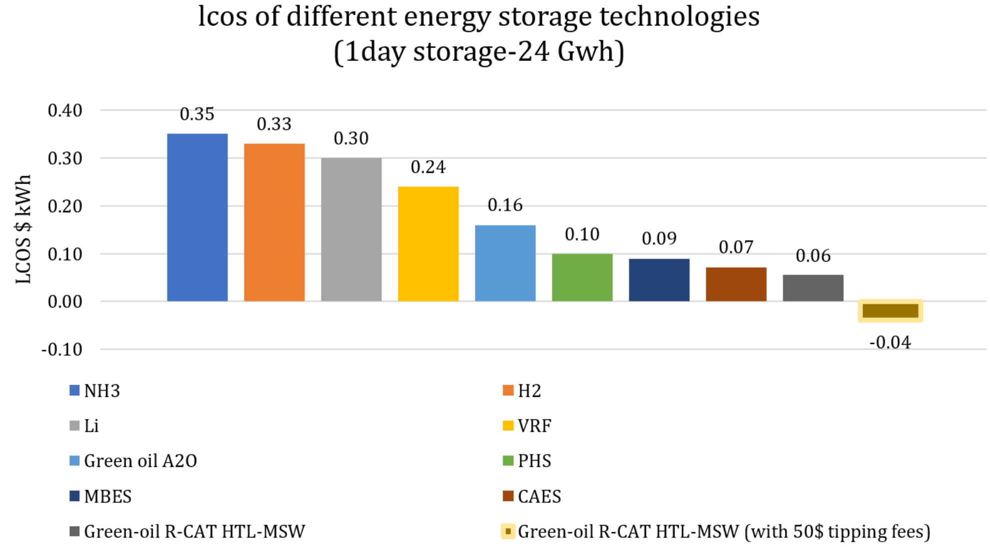
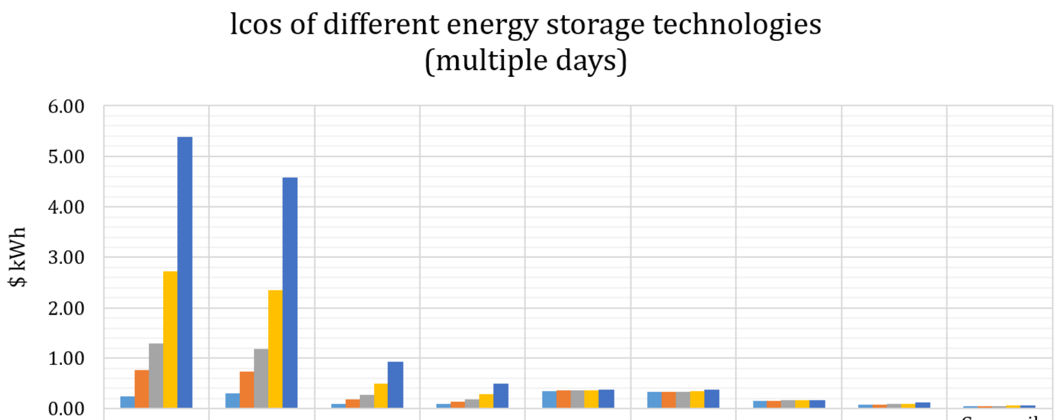


Figure 5. LCOS comparison with one day of storage for 24 GWh (various energy storage technologies).

Overall, compared with the other energy storage systems considered in this paper, pumped hydro storage, CAES, moving block and R-CAT HTL MSW green oil provide ≤ 0.10 $/kWh. Green ammonia, lithium-ion batteries, green hydrogen, VRFB, and A2O-green oil yield higher LCOSs at 0.35 $/kWh, 0.3 $/kWh, 0.33 $/kWh, and 0.24 $/kWh 0.16 $/kWh, respectively, for relatively short 1-day storage requirements.

Figure 6 compares the LCOSs for the same technologies as above for multiple day storage requirements based on the daily storage requirement of 24 GWh.



	VRF	Li	MBES	PHS	NH3	H2	Green oil A2O	CAES	Green oil R-CAT HTL-MSW
1day	0.24	0.30	0.09	0.10	0.35	0.33	0.16	0.07	0.06
4days	0.77	0.74	0.18	0.14	0.36	0.33	0.16	0.08	0.06
7days	1.30	1.18	0.27	0.18	0.36	0.34	0.16	0.09	0.06
15days	2.72	2.36	0.50	0.29	0.37	0.35	0.17	0.10	0.06
30days	5.38	4.58	0.93	0.50	0.38	0.38	0.17	0.12	0.06

1day 4days 7days 15days 30days

Figure 6. Comparison of the LCOS of various energy storage technologies for multiple days.

As expected, with longer-term energy storage to compensate for the intermittency of renewables, compared with the LCOS of one day, the LCOS of multiple days increases significantly for Li ions, VRFB, moving blocks, and pumped hydro. On the other hand, the cost increases moderately for CAES, green ammonia, and green hydrogen. However, for high-energy-density renewable green oils from MSW and A2O, the additional energy storage capacity has a minimal increase in the LCOS. As pointed out before, the cost of green oil MSW can decrease further with increasing tipping fees. The following section discusses the impact of tipping fees on green oil costs.

4.1. Reduction in the cost of green oil with increasing tipping fees

The cost of green oil from MSW is a strong function of tipping fees. Municipalities worldwide are trying to minimize landfills and more efficiently manage and valorize MSW by incentivizing waste management through increasing tipping fees. In Table 9, we summarize the impact of tipping fees (Kantner and Staley, 2019) in different regions of the world, which range from 9-85 $ per ton. The lower middle-income countries such as India have tipping fees of 9-27 per ton, upper middle-income countries have tipping fees from 15 -40 per ton, while high-income countries have tipping fees of 50-85 per ton. In low-income countries, MSW is still disposed of openly, which will get eliminated with increasing income levels. As expected, tipping fees reduce the cost of green oil production and reduces LCOS for electricity generation significantly.

Table 9. Tipping fees across various regions.

Region	Countries	Collection %	Moisture in MSW	Moisture in Organics, wt.%	Tipping Fees, USD/ton
High Income countries	US, Canada, Australia, Western EU, Nordics, Japan	96%	21%	60	50-85 USD/ton
Upper-middle income	China, Russia, South Africa,	82%	35%	65	15-40 USD/ton

countries	Brazil				
Lower-middle income countries	India, Pakistan, Bangladesh, Sri-Lanka, Nigeria	51%	35%	70	9–27 USD/ton
Low-income countries	Sub-Saharan Africa	39%	36%	70	Open dumping

The cost of renewable green oil from MSW is estimated at different tipping fees ranging from $10-80 per ton, as summarized in Table 10. The capacity of the plant is 2,000 TPD MSW, which produces 1,284 barrels of green oil per day. At tipping fees above 30 $/ton, the cost of green oil production becomes negative since the credit from the tipping fees is more than the Opex and covers 10 years for Capex pay out.

Table 10. Costs of green oil production from MSW at different tipping fees.

Tipping fee	$ ton	0	10	20	40	80
Corrected Opex	mm$	14.5	7.9	1.3	-11.9	-38.3
Green oil cost	$/bbl.	48	32	17	-15	-77

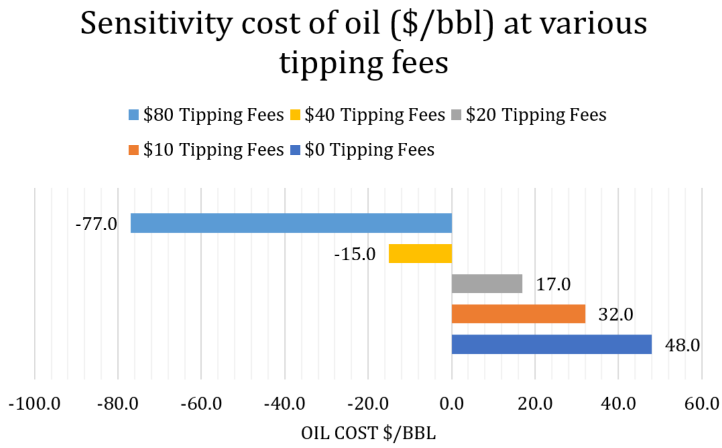


Figure 7. Sensitivity of oil cost to various tipping fees.

Figure 7 summarizes the same results graphically. Above 30 $ per ton tipping fees, the green oil production cost becomes negative. Even at 10 $ per ton of tipping fees, prevalent in lower middle-income countries such as India, the green oil production cost is only 32 $/Bbl. Any increase in tipping fees will further reduce this cost, which ultimately reduces the LCOS cost further.

Apart from its use in conventional reciprocating engines, the green oil produced from RCAT-HTL also has the potential to generate power by burning it in an advanced turbine. This approach will enable green oil to generate power in very large capacities in a single machine compared to multiple reciprocating engines. Currently, available conventional turbines have capacities > 500 MW. Such development will further reduce, to some extent, the LCOS of electricity production from green oil at a very large scale. We can also use current fossil oil-based power generation infrastructure and reduce overall new investments by replacing fossil oil with green oil.

Here, we delve into the significant contributions of our research to the field of large-scale long duration energy storage (LDLS) and intermittent renewable energy integration:

- Innovative Conceptualization of Green Oil Storage: Our paper pioneers the concept of renewable green oil as energy storage option, presenting it as a breakthrough solution for long-duration, large-scale energy storage. By introducing this novel approach, we expand the horizon of possibilities in energy storage, offering a sustainable alternative to other mechanical and electrochemical solutions.

- Economic Viability Assessment: Through an exhaustive analysis of the levelized cost of storage (LCOS), we provide compelling evidence of the economic competitiveness of green oil storage. This analysis not only underscores the feasibility of using green oil as an energy storage medium but also provides crucial insights for decision makers regarding investment strategies and policy formulation. This is an especially important option for developing economies who have recently embarked upon large scale renewable energy investments. This approach will significantly reduce cost of expensive infrastructure development required for other grass roots alternatives, as one can use existing investments in fossil oil. Here green oil will simply replace fossil oils.
- Global Perspective on Renewable Energy Integration: Our research offers a global perspective on the integration of renewable energy by examining solar PV production across different regions. By highlighting the importance of long-duration large-scale energy storage, and in addressing regional disparities in renewable resource availability, we emphasize the universal applicability of green oil as cost effective LDLS solution in achieving sustainable energy systems worldwide to combat climate change.
- Policy Implications and Pathways for Sustainable Development: The findings of our study carry significant implications for policy development aimed at advancing net zero sustainability goals at significantly reduced costs. By advocating for the implementation of long-duration, large-scale (LDLS) storage utilizing green oil, we are confident that policies promoting the production and utilization of renewable green oil will expedite the shift towards a low-carbon economy. This transition will bolster energy security and help mitigate the detrimental effects of climate change, all while offering substantial cost savings to global economies.

In summary, our research makes substantial contributions to the discourse on LSLD energy storage and intermittent renewable energy integration. Through the introduction of green oil storage and on demand electricity generation from known technologies we provide the least cost alternative for critical LSLD, we believe it will catalyze transformative changes in the energy systems landscape, at significantly reduced costs to the economies, driving us faster to a more sustainable and resilient future.

5. Conclusions

As we approach 100% clean electricity, there will be a requirement for long duration large scale (LDLS) energy storage (in terms of days, weeks, and months) to address intermittency and other seasonal shortfalls in natural renewable resources such as solar and wind. We also demonstrated, using solar PV production as an example from various global regions, that achieving 100% renewable electricity will necessitate more than 14 days of minimum energy storage. Today, solar PV projects typically provide 4-8 hr. of battery storage capacity, and no one is considering more than 1 day of energy storage for LDLS. A comparison of the levelized cost of storage (LCOS) of the different storage technologies clearly indicates that the cost of storage increases significantly with increasing energy storage capacity and duration for all mechanical and electrochemical battery technologies currently being pursued. Since renewable green oil is a stored energy with the highest volumetric energy density with lowest cost for storage and transport, it should be considered for long-duration large-scale (LDLS) energy storage. We also demonstrate that making renewable electricity from green oil produced by converting various waste organic streams, such as MSW, is an order of magnitude cheaper than other energy storage technologies. This approach will ensure the cost-effective reliability and resiliency of an electric grid at a significantly high level of intermittent renewable energy penetration on the electric grid. Green oil can be easily transported and stored using existing infrastructure. High-density green oil is stored at ambient conditions and requires less storage space, resulting in lower costs for LDLS. Since green oil can be produced at various distributed locations and can be transported cheaply, like fossil crude oil, it can play an important role in the renewable energy mix of the future, and we critically need to accelerate this transition to avoid disastrous consequences of global warming, which is an existential threat to humanity. The theoretical and practical implications of this research are as follows:

Theoretical Implications:

- Advancement of Energy Storage Theory: Our findings challenge traditional notions within energy storage theory by highlighting the critical necessity of long-duration, large-scale (LDLS) energy storage as we strive toward 100% clean electricity from intermittent renewable sources. This underscores the importance of developing new theoretical frameworks to accommodate the unique requirements of renewable energy integration into the grid.
- Rethinking Energy Economics: The comparison of levelized costs of storage (LCOS) across different technologies provides insights into the economic dynamics of energy storage at scale. This contributes to ongoing discussions in energy economics by revealing the cost implications of scaling storage capacity and duration, potentially reshaping economic models and investment strategies in the renewable energy sector.
- Integration of Renewable Energy: Our research advances theories related to the integration of renewable energy into existing grids by emphasizing the crucial role of LDLS in managing intermittency and seasonal variations in renewable resource availability. This highlights the need for innovative solutions and policy frameworks to support the transition to a renewable energy-based grid.

Practical Implications

- Policy Development: Our findings have direct implications for policy development, urging policymakers to prioritize the deployment of LDLS energy storage solutions as part of broader strategies to achieve 100% clean electricity. This necessitates the development of supportive regulatory frameworks and incentives to accelerate the adoption of innovative storage technologies such as green oil.
- Technology Innovation: This research underscores the need for continued innovation in energy storage technologies, particularly in the development of high-energy density and cost-effective solutions capable of meeting the demands of LDLS. This calls for increased investment in research and development initiatives aimed at advancing green oil production and storage technologies.
- Grid Resilience and Reliability: Utilities and grid operators can leverage our findings to enhance grid resilience and reliability by investing in LDLS energy storage with green oil as primary storage. This includes strategic production and deployment of green oil storage facilities to mitigate the impacts of intermittency and ensure a stable electricity supply even during periods of low renewable resource availability.
- Environmental Sustainability: The adoption of green oil as an energy storage medium offers significant environmental benefits by reducing reliance on fossil fuels and mitigating greenhouse gas emissions. This aligns with global efforts to combat climate change and promote sustainable development, making green oil a compelling solution for achieving both environmental and energy security goals.

  Global Energy Transition: Our research emphasizes the global significance of LDLS energy storage in facilitating the transition to a renewable energy future. By highlighting the economic viability and practical feasibility of green oil as LDLS energy storage, we provide a pathway for countries worldwide to accelerate their transition toward cleaner and more resilient energy systems, mitigating the risks of climate change and advancing sustainable development goals. This is particularly important for developing countries like India

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Conflict of interest

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

Author contributions

Ajit Sapre: Conceptualization, Internal funding support, Writing - Review & Editing. Amit Gawade: Conceptualization, Formal analysis, Investigation, Writing - Review & Editing

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