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ADVANCEMENT OF THIN FILM SOLAR CELLS

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ABSTRACT: *Solar power has come a long way with the recent developments in photovoltaic (PV) technology. The emerging PV technologies which will be commercially available like perovskite and organic solar cells, are discussed along with their pros and cons. This article reviews the recent improvements in PV accessibility, affordability, and efficiency. New materials and techniques are being researched for better and economical solar cells. A comprehensive review of thin film solar cell (TFSC) technology is presented in this study, including its manufacturing processes, classification, principles, advantages, disadvantages, challenges, and future prospects. Thin film solar cells are a promising way to efficiently harness solar energy as they are simple, have high absorption coefficients, and can be tailored to desired properties. This paper classifies solar cells into first, second, and third generations, showcasing the transition from crystalline silicon-based technologies to advanced thin film and emerging technologies like quantum dot, perovskite, and organic solar cells. Each generation is observed in terms of manufacturing processes, materials, and efficiency. The concerns in TFSC technology, including manufacturing innovation, material advancement, and efficiency improvement are discussed.*

KEYWORDS: Thin Film Solar Cells, Next Gen Solar Cell, Copper Indium Gallium Selenide, Next Gen Technology

1. INTRODUCTION

Thin film solar cells are simple in design. They are designed with one light-absorbing layer amid two conductive layers. Subsequent layers may be added to a solar cell to improve its performance by preventing energy loss at layer boundaries. This could lead to improved electron mobility and hence higher efficiency. Electron-hole pairs are created in the absorbing layer as sunlight hits the cell. Electrons move to one side due to the presence of an internal electric field creating a negative charge, while due to a lack of electrons the opposite side becomes positively charged [1][2]. With the increasing environmental concerns due to fossil fuels and growing power demands, solar energy is now considered as the most crucial renewable energy source. This energy is reliable ample, and economical in comparison to other renewable options. There are three main types of solar cells: photovoltaic (PV), organic and hybrid. PV cells are most widely used cells, trailed by hybrid and organic cells. However, conventional crystalline silicon PV cells have high production costs and low energy conversion efficiency. These issues are addressed by researchers with third-generation solar cells developed using new materials and technologies [3]. Thin-film silicon solar cells show promise but require improvements in efficiency and manufacturing processes. Solar cell efficiency can be enhanced by using plasmonic, which combines optics and nanotechnology. Researchers are able to boost light absorption by integrating metallic nanostructures like gold or silver nanoparticles. Plasmonic gratings, for example, can regulate light absorption and polarization resulting in improved efficiency. Using a plasmonic grating structure as the back metal contact in thin-film solar cells increases light path length within the cell, enhancing absorption. Efficient light trapping combined with surface Plasmon resonance can significantly improve solar cell efficiency. Advanced models are also needed to better understand photovoltaic cell behaviour under different conditions, which will help further solar energy technology advancements and promote widespread adoption [4][5]. The advantages and disadvantages of PV Cells are as follows:

- **ADVANTAGES**

  (1) High radiation tolerance
  (2) High specific power; potentially in the kilowatt/ kilogram range
  (3) Large area solar cells with integral series interconnections
  (4) Flexible blankets
  (5) Large (by spacecraft standards) body of array manufacturing experience
  (6) Low cost

- **DISADVANTAGES**

  (1) Lower efficiency

(2) Lack of spacecraft experience
(3) Not currently produced on lightweight substrates [6]

This paper is organized as follows: Section 2 presents history of PV cells for better understanding**.** **S**ection 3 discusses classification of solar cells based on their generation**.** PV system components and next generation tech are presented in section 4 and 5**.** Section 6 finally concludes this study.

2. HISTORY

Back in 1954, scientists stumbled upon something ground breaking: the photovoltaic effect in certain compounds, specifically CdS/Cu2-xS heterojunctions [7]. The discovery of the photovoltaic effect in CdS/Cu2-xS heterojunctions in 1954 coincided with Bell Labs' announcement of crystalline silicon cells, marking a milestone for solar technology. Thin film solar cell development began with evaporated CdS films in the USSR, leading to experimentation with CdTe in the 1960s and 70s. Techniques like post-deposition treatments and chlorine addition helped CdTe cells to surpass 10% efficiency in the late 1980s [8][9][10]. The efficiency was further improved to 15.8% in 1993. The costs were further reduced in 1990s due to commercial developments with companies like First Solar and BP Solar. General Electric made notable contributions before transferring their IP to First Solar. By 2012, First Solar achieved a 17.3% efficiency record with ZnTe contact [11][12].

3. CLASSIFICATION of SOLAR CELLS

On the basis of classification, Cells are divided in three types as depicted in fig.1.:

1. First generation Solar Cells
2. Second generation Solar Cells
3. Third generation Solar Cells

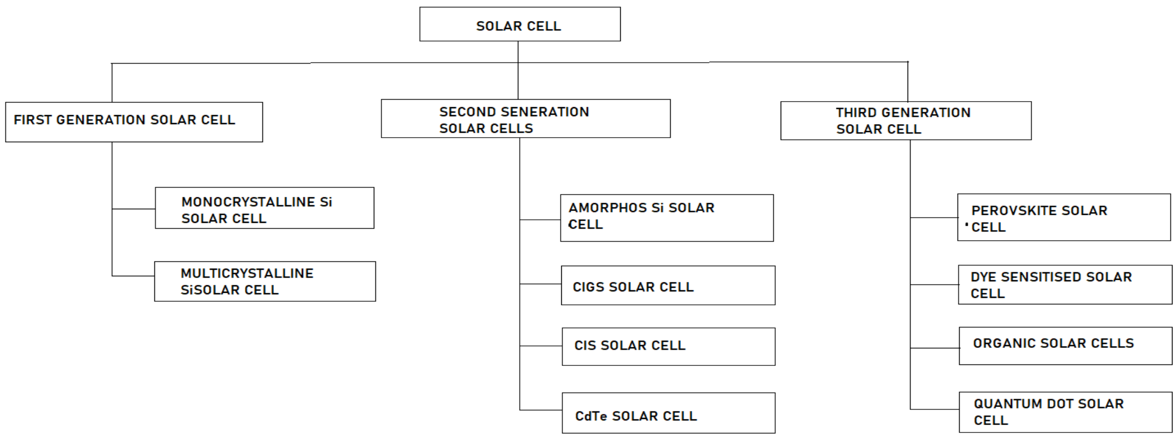

Fig. 1: Classification of solar cell [13]

- **FIRST GENERATION**

The first type of solar cells, known as first-generation solar cells, use crystalline silicon wafers. These were very popular, covering about 80% of the solar cell market because they were quite efficient at converting sunlight into electricity. However, they were also quite expensive to make. There were two main types of first-generation solar cells: single-crystalline silicon and multi-crystalline silicon. Single crystalline silicon cells were very effective, but they got less efficient as they got hotter, which was a problem. Multi-crystalline silicon cells were cheaper to produce but were a bit less efficient [13]. Over the past twenty years or so, there has been a lot of progress in developing what's called second-generation solar cell technology. Different materials and techniques used in these cells have curtailed the demand for expensive silicon wafers. On comparison with first generation, second-generation solar cells are more efficient and economical [13] [14].

- **SECOND GENERATION**
    - **Amorphous Silicon Solar Cells**.

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Amorphous silicon, often called a-Si, with its special property of direct band gap is used in solar cells and LED displays. The structure of a-Si is more haphazard unlike regular structured silicon as shown in fig.2. This makes it less efficient at capturing sunlight. Hydrogenation process can improve this random structure and makes the silicon more manageable and less defective. However, Concerns like light-induced degradation appear over time with the addition of hydrogen atoms. The other alternative to make the cell more efficient is to add carbon to the mix resulting in better conductivity [15][16].

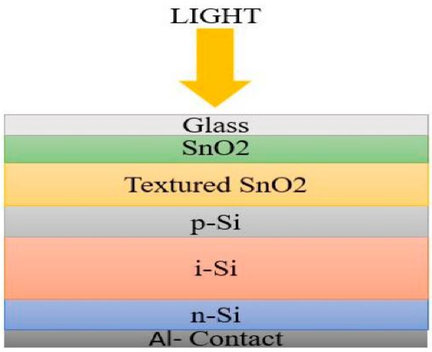

Fig. 2. Substrate configuration [15]

- **CIGS Solar Cells**

Copper Indium Gallium Selenide (CIGS) is a material used in solar cells because of its strength of absorbing sunlight. It's made of copper, indium, gallium, and selenium. The efficiency in converting sunlight into electricity directly depends on the amount of each element used. When we pair CIGS with another material called CdS, the solar cell still works well, even if there are some imperfections in the materials [17]. CIGS cell architecture is illustrated in fig.3. If we want to calculate the bandgap of CIGS with its active material structure CuIn (1-x) GaxSe2, we can use a mathematical equation.

$$Eg = 1.01 + 0.626x - 0.167x(1 - x)\ \text{eV} \qquad \ldots (1)$$

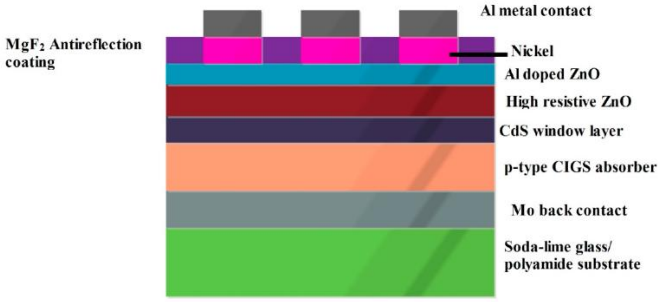

Fig. 3. Diagrammatic representation of CIGS cell architecture [17].

CIGS solar cells can be used instead of traditional silicon solar cells in some cases. They are durable, flexible, and can be made to fit into things more easily during manufacturing., The focus is on the thickness of the CdS layer and mobility of charge carriers to make CIGS solar cells work better. Hence, the CdS layer is kept thin to absorb more sunlight and makes the solar cell more efficient. When sunlight hits the solar cell, the CdS buffer layer allows the light to pass to the CIGS layer, where excitons are made. Because of the electric field in the cell, electrons move in one direction and holes move in the other. A back surface field helps send any stray electrons back to where they're supposed to be [18].

- **CdTe Solar Cells**

Cadmium Telluride (CdTe) is a used in solar cells. Selenium is sometimes added during manufacturing to make it work better by allowing it to absorb different kinds of sunlight. The cell is graphically represented in fig. 4. These materials are heated at high temperatures during the process. When we make CdTe solar cells, we usually start by putting down a layer of CdS, which helps collect the energy made when sunlight hits the CdTe. The solar cell becomes inefficient if this layer is too thick. Hence, the thickness is controlled carefully [19]. Chemical bath or sputtering are few of the many different ways to put down the CdS layer. Mg1−xZnxO material is also used by some researchers instead of CdS. CdTe is usually made up of lots of small crystals. The way we make the CdTe layer can affect how well the solar cell works, with some methods being better than others. The issue with CdTe solar cells is to connect the back part connect correctly. Some materials work well for this, but they can react with the CdTe. Therefore, alternate materials are being searched to avoid problems. CdTe solar cells are generally stable, but they need to be protected properly. If copper gets into them, it can make them work less effectively. But we can use other materials to stop this from happening [20].

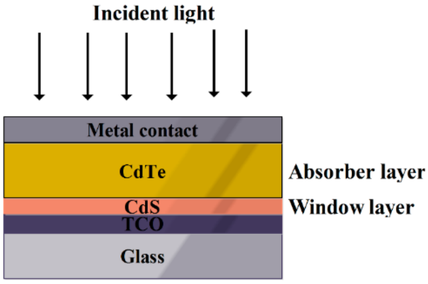

Fig. 4. Pictorial representation of simple CdTe SC [19]

- **THIRD GENERATION SOLAR CELLS**
  - **Dye sensitised Solar Cells**

A dye-sensitized solar cell (DSSC) is like a mini power plant inspired by photosynthesis in plants. A photo-electrolyte, a transparent conductive oxide (TCO) electrode, a titanium dioxide (TiO2) electrode, and protective glass casing are used to prepare this cell. The dye molecules in the electrolyte get energised when comes in the contact of sunlight. These excited molecules then pass their electrons to the titanium dioxide molecules, making them produce electrons and oxidize the dye. Unlike regular solar cells, DSSCs work a bit differently. The sunlight get absorbed directly by the dye molecules and not into the material. Electricity starts flowing on the generation of the electrons that move through the system [21]. The performance of DSSCs depends on things like the type of dye used, how the electrode is set up, and the properties of the electrolyte.[22]

  - **Perovskite Solar Cells**

Perovskite solar cells (PSCs) as shown in fig. 5, are known for their unique properties and impressive performance. The ABX3 architecture, where A, B, and X represent different elements, allows for tuneable band gaps and high absorption coefficients, making perovskite materials versatile for various applications, including LEDs and photodetectors. The different elements in these cells are organized in a way which decides their working and their power of absorbing sunlight. This makes them useful for things like LEDs and sensors [23].

Fig. 5. Perovskite Architecture [23]

  - **Organic Solar Cells**

Organic semiconducting polymers have distinct molecular structures with strong σ-bonds along the carbon chain and weaker π-bonds at the edges. Architecture of these cells isd shown in fig. 6. It has been discovered by researchers that inverted architectures can sometimes lead to higher power conversion efficiency. The outer bonds of these polymers are primarily utilised to conduct electricity. Other elements on incorporation can enhance this conductivity. Polymers like polypyrrole and polythiophene are crucial in electronic devices. It is easier to manufacture polymeric solar cells than small molecule-based cells. In organic solar cells, a strong electric field is required to separate as excitons have limited mobility. Despite challenges, their lab adaptability makes them promising for future energy projects [24].

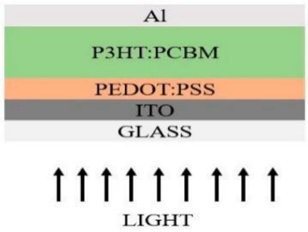

Fig. 6. Architecture of Organic cells [24]

- **Quantum Dot Solar Cells**

Quantum dot solar cells (QD SCs) have shown promise in enhancing the photo generation process through carefully designed arrays of quantum dots. Structure of this cell is portrayed in fig.7. Researchers have extensively studied CdX as it exhibits improved electrochemical and optical properties, where X can be elements like S, Se, or Te. QDs, which respond to incident light, have been fabricated from semiconducting materials to achieve higher performance with easily tunable energy band gaps. Nanostructures like Nano sheets, Nano rods, and nanowires have been developed to transform these materials. When light hits the QDs, they become sensitized, and the redox electrolyte adheres to their surface, facilitating electron and ion movement [25]. Some of the recent developments on Cells are reported in table 1.

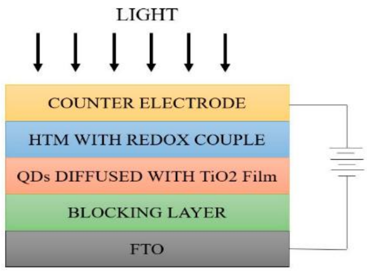

Fig. 7. Architecture of QD SC. [25]

RECENT DEVELOPMENT ON CELLS

Table 1. Performance parameters of various landmark cells [26][27]

Record/Notable Cell	AM1.5 Efficiency (%)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Effective E_g from IQE (eV)	$V_{oc,SQ}$ (V)	V_{oc} Deficit ($V_{oc,SQ}$ - V_{oc}) (V)[a]	Notes
USF 1993	15.8	25.1	0.843	74.5	1.48	1.214	0.371	CdS/CdTe
NREL 2001	16.7	25.9	0.845	75.5	1.48	1.214	0.369	Cd_2SnO_4/Zn_2SnO_4/CdTe
GE 2012	18.3	27.0	0.857	79.0	1.48	1.214	0.357	CdTe absorber
FSLR 2012	18.7	28.6	0.853	76.7	1.45	1.186	0.333	CdTe absorber
FSLR 2014	22.1	31.7	0.887	78.5	1.39	1.130	0.243	CdSeTe absorber
ASU 2016	17	22.3	1.036	73.6	1.48	1.214	0.178	Epitaxial CdTe double heterojunction absorber
NREL 2016	13.6	21.7	1.017	61.7	1.48	1.214	0.197	Poly CdS/P-doped CdTe single crystal wafers
25% Targets	25.0	**32.0**	**0.975**	**80.0**	**1.39**	1.130	**0.155**	Multiple combinations of bandgap and JV parameters can achieve 25%
		31.7 …	0.956 …	82.5 …	1.39 …	1.130 …	0.174 …	

4. PV SYSTEM COMPONENTS

The main components of a PV system are PV module, power electronics (for power conversion), Energy storage device, grid and load. Various materials are being used nowadays to improve the overall efficiency of the cells. All the components along with advanced materials are illustrated in the fig. 8. To maximize light absorption in solar panels and to minimize reflection, coatings are used.[28]

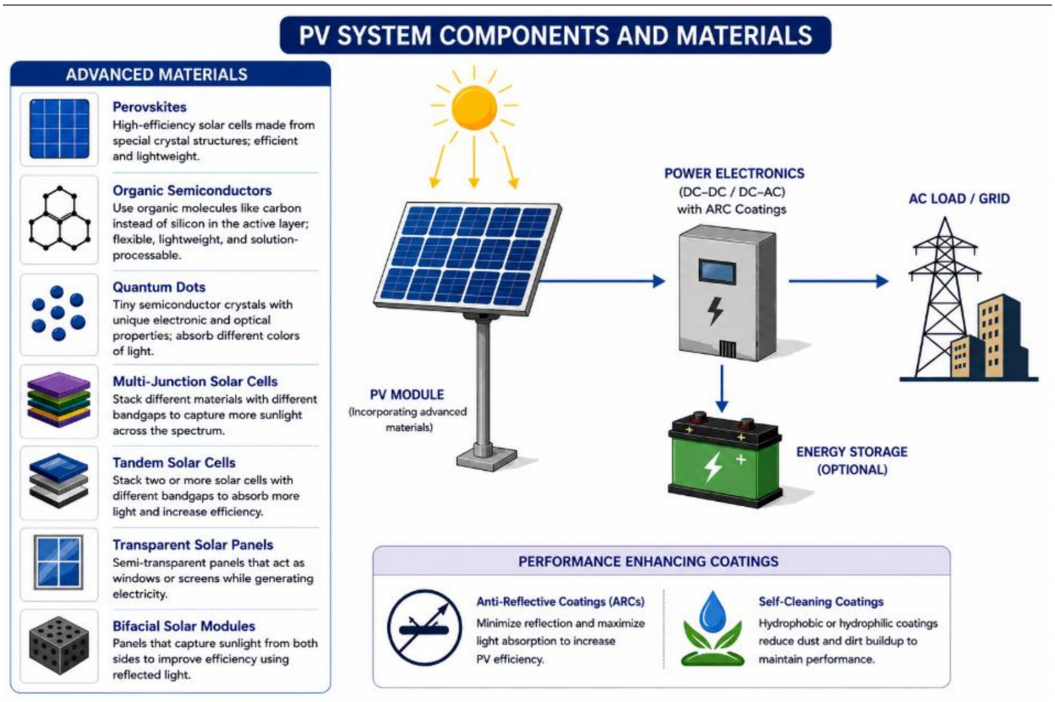

Fig. 8. Components of PV system and Advanced materials used.

- **Solar Tracking**

  Solar tracking in PV panels is a mechanism in which solar panels are adjusted to follow the path of the sun throughout the day for better sunlight capture and increased energy yield. Traditional fixed solar panels are oriented in a fixed position, while single-axis and dual-axis trackers can move to track sun. Single-axis trackers can move either horizontally or vertically. Horizontal trackers are suitable for sunny areas near the equator, while vertical ones work best in places with longer summer days and lower sun angles. Dual-axis trackers can move in both horizontal and vertical directions, allowing them to precisely track the sun's path anywhere in the world. They provide even more power output and are ideal for maximizing sunlight capture in all locations. The solar tracker classification along with its working is depicted in fig. 9.

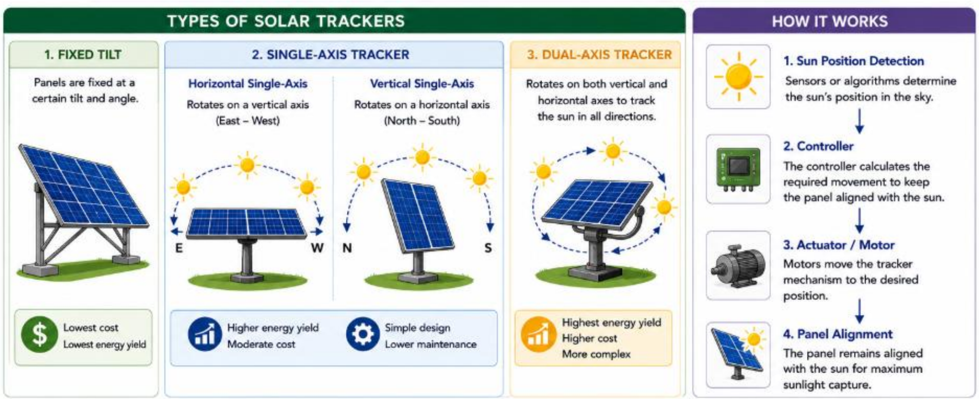

Fig. 9. Classification and working of solar trackers.

- **EFFICIENCY OF DIFFERENT MATERIAL IN 1993-2021**

The evolution in cell efficiency for different materials over the last few decades is analysed and tabulated as follows in table 2.

Table 2: Cell Efficiency

DEVELOPMENT OF LAB SOLAR CELL EFFICIENCIES (in%)									
		MATERIALS	Organic	Perovskite	CdTe	CIGS	Multi Crystaline Silicon	Mono Crystalline Silicon	III-V Multi junction
	YEARS								
1	1993				16	14	17	23	33
2	1995				16.2	14.2	17	24	33.2
3	1997				16.4	16	18	24.4	33.4
4	1999				17	17	20.1	24.8	33.4
5	2001				17.5	17.1	20.4	25	34.5
6	2003				17.6	17.3	20.8	25	35.6
7	2005		3		17.6	17.7	20.8	25.2	37
8	2007		5		18	18	21	25.3	39
9	2009		7		18.1	19	21.4	25.6	41
10	2011		8		19	19.5	21.5	25.9	42.3
11	2013		11		19.4	19.7	22	26.2	44.6
12	2015		13	15	20.2	20	22	26.4	45.2
13	2017		14	20	21	21	23	26.7	46.7
14	2019		15	22	21	23.4	24.4	26.7	46.8
15	2021		15.2	23.7	21	23.4	24.4	26.7	47.1

5. NEXT GENERATION TECH

In future we can use some of the following materials for making efficient use of Solar Cells

- Ultrathin Silicon: Scientists are finding that making single-crystal silicon cells thinner boosts their efficiency. In fact, they've found that a thickness as low as 2 micrometers can lead to really powerful solar panels. These thin cells are also tough against radiation damage.

- Indium Phosphide: There's a lot of excitement around a material called indium phosphide (InP) because it's super-efficient at turning sunlight into electricity. It's also more resistant to damage from radiation than other materials, but it's pretty expensive.

- Single-Crystal Film Technologies: Another idea is to grow a thin layer of single-crystal semiconductor on a thick base, then make solar cells from that layer and peel it off the base. This method has produced super-efficient solar cells on really thin layers of material.

- High Efficiency Cascades: Some researchers are stacking different materials together to make super-efficient solar cells. They've even achieved an efficiency of over 20% by combining different types of materials.

- Concentrators: Another way to boost efficiency is by using mirrors or lenses to concentrate sunlight onto the solar cells. This can increase efficiency, but it comes with its own set of challenges [6].

6. CONCLUSION

The study highlights the growing importance of thin film solar cells over traditional silicon-based cells in the photovoltaic market due to their higher efficiency and lower production costs. Researchers are making progress in spite of challenges like parasitic absorption and limited carrier lifetime. There are most efficient thin film cells available now achieving over 20% efficiency using Cu(In,Ga)Se2. New materials like Cu2ZnSn(S,Se)4 are also being explored. Various thin film technologies are heading towards practical applications including those based on amorphous silicon and chalcogenides. Second and third-generation solar cells are being researched for their unique properties. Emerging technologies like plasmon-induced resonance energy transfer (PIRET) and plasmonic nanostructures are being studied to enhance efficiency by improving energy transfer and light absorption. Future advancements in single-crystal films, indium phosphide, ultrathin silicon, high-efficiency cascades, and concentrators indicate potential for further enhancements in solar cell performance, making renewable energy more accessible and sustainable.

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