Research Progress of potential solar cells alternative

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Abstract. With ongoing advancements in solar cell research, new generations of solar cells are increasingly demonstrating superior efficiencies. However, the application of theoretical advancements to practical experiences has seen limited realization, with significant barriers being encountered, notably in the realms of commercialization and manufacturing of novel cells, such as perovskites. This paper analyzed the potentialities and advancements of emerging solar cell technologies, providing a nuanced comparative analysis to assess the technological progression and potentials inherent in them. The exploration commences from the first-generation silicon crystalline cells and navigates through to the innovative third-generation perovskite cells. This journey reveals distinct material properties and sophisticated optimization strategies, each precisely focused on achieving enhanced efficiency. To facilitate a deeper comprehension of the limits and distinctive advantages of each solar cell type, an extensive analysis of their industrial development processes and specific technological attributes is undertaken. A representative comparative illustration will be furnished for each solar cell type, accentuating their stability, material characteristics, supply dynamics, developmental statuses, and environmental impacts. This investigation encompasses a foundational analysis across the three generations of solar cells, attributing to each generation a unique cell type to illuminate possible development directions and existing challenges, thereby, defining prospective pathways to navigate current constraints. The commercialization challenges inherent to alternative solar cells are elaborated, providing reflections on the probable future research trajectories and industrial manufacturing approaches. This discourse aims to afford a thorough and insightful understanding of the potential breakthroughs and impediments in the evolving landscape of solar cell technologies, balancing technological advancements, practical implementations, and environmental considerations.

Keywords: Silicon solar cells, thin-film solar cells, perovskite.

1. Introduction

With significant global advancements in solar technology, silicon-based solar cells have dominated the market due to their refined manufacturing processes, escalating efficiency, and cost-effectiveness. Notably, mono-crystalline silicon and related solar cells have secured an installation rate exceeding 80%, commanding 90% of the market share. This dominance can be attributed to the longstanding developmental feedback and a steady supply from associated microelectronic industries, particularly the semiconductor sector [1]. However, as semiconductor resources diminish over time, the reliance on silicon-based solar cells could become a concern. While the theoretical efficiency limit for monocrystalline cells, as posited by Shockley and Queisser, was once pegged at 30%, modern cells approach this threshold, currently standing at approximately 26% [2]. Second-generation thin-film solar cells, despite their reduced thickness and cost, haven't garnered a significant market presence. They currently represent less than 5% of the market, on par with promising third-generation alternatives like perovskites [3].

Furthermore, while advancements in solar cell technology are evident, a substantial practical experience gap exists. For example, CdTe solar cells underwent a notable efficiency transformation within a decade, from 16% in 1993 to 22.1% in 2001 [4]. Recent contenders like perovskite cells exhibit tremendous energy potential, with heterojunction solar cells even surpassing previous efficiency benchmarks. However, despite the environmental benefits of these advancements, numerous alternatives remain in experimental phases, primarily due to market reluctances. A significant portion of solar cell manufacturing, particularly mono-crystalline silicon cells, is concentrated in China, driven by policies aimed at reducing production costs [5]. This paper, while acknowledging the prominence of mono-crystalline silicon solar cells, aims to evaluate alternative thin-film and newer generation solar cells. Through this comprehensive analysis, the paper seeks to underscore the challenges confronting the commercialization of alternative solar cells. Recommendations for commercialization strategies will be proposed, and potential future research trajectories will be outlined.

2. Silicon Based and Other First Generation Solar Cells

From their inception, solar cells were recognized for their potential cost-effectiveness. This potential was realized through the excitation of photons moving electrons to generate voltage and achieving an appropriate bandgap for efficient current creation. Ideally, a solar cell should possess a bandgap between 1.1 and 1.7 eV, a direct band structure, accessibility, and a suitable voltage. Silicon emerged as an optimal choice for these criteria, with its earliest development at Bell Labs [1].

Subsequent innovations, like surface texturing, screen printing, and the passivated emitter and rear contact, have shaped the contemporary silicon solar cell market. The period of industrialization saw a consistent rise in the commercialization of these solar cells, with further efficiency enhancement programs emerging from the 1900s to 2000s. Notably, the first-generation silicon solar cells have achieved an efficiency record of 26.3% as reported by Kaneka, Japan. Yet, there remains untapped potential in silicon solar cells, hinting at several more decades of research and development [6].

The first-generation category encompasses monocrystalline silicon (M-Si), polycrystalline silicon (P-Si), and GaAs. Several solar cell technologies have been developed to bolster the efficiency and utility of silicon-based cells: (i) Monocrystalline Silicon (M-Si): These cells are manufactured using silicon wafers created from silicon blocks grown from seeds using the Czochralski process. With high material purity, they achieve efficiencies between 15% to 24%, albeit with significant silicon consumption [7]. (ii) Polycrystalline Silicon (P-Si): Achieving efficiencies of 10-18%, these cells are favored for their relatively straightforward manufacturing process, which results in cost savings [7]. (iii)GaAs: Distinguished by its direct band, GaAs ensures minimal energy wastage and boasts impressive efficiencies between 28% to 30%. However, its higher cost poses challenges for broader commercialization [7].

Over time, multiple technologies emerged to push the boundaries of silicon solar cell efficiency: (i) Passivated Emitter Rear Cell (PERC): This technology achieves approximately 22% efficiency. By employing a passivation film, PERC combats potential losses, compensating for larger thickness and reducing internal reflection [6]. (ii) Interdigitated Back Contact Cell (IBC): Promising for large-scale industrial production, these cells, fabricated using n-type substrates with boron-diffused emitters, have reached an average efficiency of around 23%, with lab results showing up to 25% [6]. (iii) Heterojunction Solar Cells with Interdigitated Back Contacts (HBC): Among the highest in efficiency, these cells incorporate the interdigitated back contact into the heterojunction structure. Silicon nitride doping reduces energy losses from reflection, with a current record efficiency of 26.3% by Kaneka [6].

Crystalline silicon (c-Si) solar cells have consistently been at the forefront of the photovoltaic sector, inching closer to their intrinsic efficiency limits. Current scientific evaluations, when considering Lambertian light trapping and excluding defect-induced recombination, anticipate a maximum efficiency of about 29%, notably observed at an 80-μm thickness. As these limits are approached, the community is presented with a timely question about the trajectory of solar research. While diverse methodologies align in their findings on the electronic transport properties of c-Si solar cells, it remains evident that the inherent limitations of c-Si are nearing. The exploration of tandem structures, aiming to potentially achieve efficiencies around 40%, underscores the ambition of the field. The promise of perovskite/silicon and III-V/silicon multi-junctions is undeniable. However, there is a broader landscape to consider [2].

Beyond the noteworthy advancements in perovskite-based cells, the research landscape has identified a plethora of organic and alternative materials that present commendable prospects. These materials are not merely propitious in terms of energy conversion efficiency; they also resonate well with contemporary environmental paradigms due to their minimal ecological footprint. Distinctive attributes of materials, including perovskite and specific organic photovoltaic compounds, encompass their diminished manufacturing implications, rapid efficiency ascendancy, and innate environmental sustainability.

Among these, III-V junction GaAs-based solar cells from the first generation serve as a paradigmatic example. Such single III-V junctions, with a foundational reliance on GaAs, have accomplished a substantial efficiency of 29.1% under singular sunlight exposure. Remarkably, when fabricated into a six-junction configuration, these cells reach an efficiency pinnacle of 47.1% under concentrated sunlight conditions. Furthermore, their inherent thinness, with absorption layers typically ranging from 2 to 5 µm, lends them a unique lightweight and flexible character, opening avenues for applications on non-planar surfaces. With a legacy rooted in high-performance scenarios such as space applications, the resilience and stability of these III-V devices are undeniable. However, it is imperative to acknowledge that, while these cells manifest myriad benefits, there remain environmental challenges associated with their fabrication and lifecycle. These challenges, although significant, do not overshadow the considerable merits of these solar cells, positioning them as viable candidates in the quest for sustainable energy solutions. Historically, the quintessential deposition process for III-V layers, the metal-organic vapor phase epitaxy (MOVPE), has been acclaimed for establishing numerous performance benchmarks for III-V based devices. However, the process was often viewed with a tinge of skepticism owing to its elevated precursor costs and extended batch growth cycles. Contemporary research endeavors have rendered this skepticism obsolete, amplifying the growth rate and enhancing precursor chemical utilization. Both MOVPE and the emergent hydrogen vapor phase epitaxy (HVPE) methodologies have showcased these advancements, with the latter addressing the precursor cost dilemma efficaciously. However, it is noteworthy that the current finishing protocols incorporate several labor-intensive, cost-heavy, and relatively inefficient procedures, spanning photolithography, manual spin-coating applications, precise contact alignments, and intricate processes of metal evaporation and lifting [7].

3. Second Generation of Solar Cells

Second-generation photovoltaics have judiciously integrated first-generation technologies, with a particular emphasis on advancements in thin-film processing techniques. Thin-film solar cells, while initially heralded for their cost-effectiveness and adaptability, faced challenges due to their initial lower efficiencies. Nonetheless, the recent years have witnessed remarkable improvements [7].

Among these, the amorphous silicon solar cell (a-Si) stands out. Characterized by its non-crystalline structure, it's founded on a fluorine-doped tin oxide (SnO_2: F) substrate situated on glass. This foundation is further enhanced with a coating of silver (Ag) and gallium-doped zinc oxide, reducing reflectivity. The evolved version employs hydrogenated a-Si, achieved via plasma-enhanced chemical vapor deposition (PECVD) using a specific blend of dopant gases. This innovation is further accentuated by an accompanying transparent conducting oxide layer and a silver grid electrode. Notably, recent specifications for a-Si reveal an efficiency of 14.04% over a 1.05 cm^2 area, complemented by an open-circuit voltage (Voc) of 1922V. However, in spite of these advancements, there's an evident need for further efficiency enhancements, especially in refining deposition methodologies apt for mass production. Additionally, other noteworthy thin-film approaches encompass metal-based solar cells, notably copper indium gallium selenide (CIGS), cadmium telluride (CdTe), copper zinc tin sulfide (CZTS), and gallium arsenide (GaAs) cells [3].

Copper Indium Gallium Selenide (CIGS) solar cells incorporate various layers, namely the substrate, back contact, absorber, buffer, and transparent conducting oxide (TCO) layer. The substrate can be rigid or flexible, with the back contact typically made of molybdenum, enhancing light absorption. The absorber layer, central to the cell, is composed of the Cu (In, Ga) (Se, S)$_2$ compound, with a thickness of around 2 μm. A buffer layer, often of cadmium sulfide, is positioned over the absorber, while the TCO layer features an aluminum-doped ZnO (ZnO: Al) coat. This composition fortifies the cell against external damage. A notable efficiency milestone of 23.35% was achieved in 2019 using a Cd-free Zn (O, S, OH) $_x$/$Zn_{0.8}Mg_{0.2}O$ double-buffer layer. Yet, challenges persist, particularly due to the rarity of indium and associated environmental concerns. Alternatives like CZTS may offer solutions, but substitutions with Zn and Sn potentially compromise efficiency, with current values around 12.6% [3].

CdTe cells, initially developed with substrate configurations, have transitioned to superstrate structures. These cells feature a zinc-blend crystal structure on standard, heat-strengthened soda-lime glass. The TCO layer, crucial for transparency and electrical conduction, comprises materials like SnO_2: F (FTO) and In_2O_3: Sn (ITO). The buffer, traditionally a window layer, is made of n-type CdS and is around 100 nm thick. This is followed by the p-type CdTe absorber layer, roughly 5 μm thick, designed to harness sunlight. The back contact, responsible for directing generated electricity, utilizes metals like Al and Mo. Despite promising efficiency records nearing 22.1%, challenges arise from material scarcity, fire risks, and potential toxicity due to the presence of heavy metals [3].

CdTe cells present notable advantages, such as reduced open-circuit voltage decline with temperature increases, making them ideal for hotter climates. Additionally, they exhibit a minimal environmental impact, emphasized by multiple studies. The low cadmium leakage and limited emission risks, even in fires, underscore their safety. Furthermore, their recyclability showcases them as a sustainable option. With an emphasis on systematic CdTe doping, the potential to approach efficiencies of 25% exists, highlighting a positive trajectory for the technology [8]. As such, CdTe could serve as a sustainable and cost-effective solar cell alternative, given continued research and optimization.

4. Third Generation Solar Cells

Third-generation solar technologies are broadening the horizons of photovoltaics, not only by enhancing efficiency or reducing costs but often striking a balance between the two. Among these advancements, organic solar cells, perovskite solar cells, dye-sensitized solar cells (DSSC), and quantum dots solar cells stand out [7].

DSSCs are particularly intriguing due to their unique structure and operational mechanism. Comprised of a photoanode with a porous layer of TiO_2 or ZnO nanoparticles anchored onto a transparent conducting film-coated glass substrate, they also feature a dye monolayer adhered to the TiO_2. This assembly complements an electrode back contact on a separate transparent conducting film-coated glass substrate and an intervening electrolyte layer with an iodine redox mediator. What sets DSSCs apart is their ability to absorb photons while simultaneously facilitating carrier transport. The operational sequence initiates with the excitation of dye molecules by photon absorption, leading to electron transfer to the conduction band of TiO_2, culminating in dye oxidization. These electrons traverse the TiO_2 matrix to reach the back contact. Meanwhile, the electrolyte layer serves the vital role of reverting the oxidized dye molecules back to their ground state. Intriguingly, this mechanism, driven by organic dyes, mirrors photo-electrochemical processes observable in natural photosynthesis. Though DSSCs hark back to concepts introduced in 1972, their contemporary significance arises from their potential advantages. Their ability to manifest as both transparent and flexible structures, their cost-effectiveness derived from the use of economical materials and streamlined fabrication methods, and their resilience under diminished irradiance earmark them as prime candidates for building-integrated photovoltaics and indoor utility. Furthermore, the aesthetic adaptability of DSSCs offers architects a photovoltaic solution that can be seamlessly integrated into visually pleasing designs. Yet, a primary constraint remains: their efficiency caps at a modest 13%, posing a challenge to their commercial expansion. A deeper dive into the material science of DSSCs, focusing on optimizing nano-electrodes and establishing robust, flexible support structures, could unlock their potential in niche markets [9].

For Quantum dot solar cells (QDSC) utilize semiconductor nanoparticles, called quantum dots, to improve solar energy conversion. The size of these quantum dots dictates the energy of photons they can absorb, allowing for tailored band gaps that can harness multiple parts of the solar spectrum. This feature is especially beneficial in multi-junction devices. Quantum dots offer potentials like multiple exciton generation, enhanced photon absorption, and improved photovoltaic (PV) cell efficiency. Methods to introduce quantum dots into PV cells include sensitizing wide band-gap semiconductors, integration with conducting polymers, or creating closely coupled QD arrays. While structurally similar to dye-sensitized solar cells, QDSSC have a low production cost, with the focus of current research being on material selection and engineering. Despite the potential, current QDSC efficiencies haven't surpassed single-junction silicon cells. However, within a decade, they've jumped from ~3% to over 16% efficiency. Colloidal quantum dots offer a low-cost, simple fabrication approach to QDSCs. To address the challenge of low photon absorption, researchers are exploring growth optimization of QDs, structural design improvements, and light trapping techniques. The possibility of exceeding standard efficiency limits using multiple exciton generation in quantum dots is a significant area of research. Yet, current devices have only shown marginal efficiency improvements in this respect. While QDSCs hold promise, they haven't yet rivaled the efficiency of conventional silicon-based cells, leading some to remain skeptical about their commercial viability [9].

Quantum dot solar cells (QDSC) harness semiconductor nanoparticles, known as quantum dots, to augment solar energy conversion efficiency. Their unique attribute, the ability to tailor band gaps based on size, allows them to capture diverse parts of the solar spectrum, proving invaluable in multi-junction devices. Quantum dots are celebrated for capabilities such as multiple exciton generation, heightened photon absorption, and enhancement in overall PV cell efficiency. Current integration strategies range from sensitizing wide band-gap semiconductors to partnering with conducting polymers and forming dense QD arrays. While QDSCs bear a structural resemblance to dye-sensitized solar cells, their cost-effectiveness stands out, especially due to the economical production of colloidal quantum dots. However, the efficiency of contemporary QDSCs hasn't surpassed that of single-junction silicon cells, despite a leap from around 3% to over 16% within a decade. Research pivots on overcoming the inherent low photon absorption, refining QD growth, optimizing structural design, and innovating light capture methods. The tantalizing potential of quantum dots to breach conventional efficiency ceilings has spurred research, but gains remain modest. Despite the promise of QDSC technology, their efficiency lags behind traditional silicon-based cells, causing market dominance skepticism [9].

Perovskite Solar Cells (PSCs) have garnered significant attention within the photovoltaic research community, primarily attributed to their noteworthy properties coupled with their cost-efficient and streamlined manufacturing processes in comparison to traditional solar cells. Derived primarily from Pb or Sn-based materials, PSCs exhibit a crystalline structure reminiscent of the innate perovskite mineral. Characterized by a low trap density, ambipolar charge transport, expansive band absorption, and commendable charge carrier diffusion lengths, PSCs present themselves as formidable contenders in solar applications. A distinctive feature of these cells lies in their tunable band-gaps, a characteristic they share with Quantum Dot Solar Cells (QDSCs). This inherent flexibility, combined with economic viability, underscores their potential in the realm of high-efficiency multi-junction solar cells. In theoretical constructs, certain metal halide perovskite multijunction designs have the potential to attain efficiencies oscillating between 32% and 35%. In a notable achievement, a tandem cell amalgamating perovskite and silicon documented an efficiency of 29.1% in 2020. The photovoltaic domain also witnesses an emerging inclination towards bifacial perovskite designs. An avant-garde model postulates a four-junction, three-terminal silicon-perovskite bifacial cell, adept at harnessing ambient reflected light, aiming for efficiencies in the 30%-36% bracket. However, PSCs are not devoid of challenges. Their spectral utilization is not exhaustive, particularly in the UV and

IR segments. Innovative methodologies, such as spectral down-shifting–exemplified by a study employing $ZnGa_2O_4:Eu^{3+}$ nanophosphors in a mesoporous PSC, have showcased a promising elevation in efficiency by 14.34%. The malleability of PSCs offers an advantage over conventional rigid counterparts, yet issues of stability and reproducibility persist. Contemporary strategies, such as the integration of inorganic cesium cations, aim to bolster the stability of these cells. Nonetheless, hurdles related to manufacturing stability and current-voltage hysteresis endure. Moreover, environmental concerns linked to the incorporation of lead in numerous perovskite compositions have ignited a drive towards lead-free perovskite investigations [9].

In evaluating the life cycle, while silicon solar cells tout high efficiencies, they simultaneously exhibit suboptimal environmental performance, characterized by substantial energy consumption during fabrication and the intensive utilization of raw materials. Second-generation panels, to some extent, manage to modulate their environmental footprint. However, looming concerns related to freshwater ecotoxicity, marine ecotoxicity, and human noncarcinogenic toxicity remain pronounced. In this light, the third generation emerges as a potential environmentally amicable alternative [10, 11]. And all high efficiency solar cells are shown in the table 1.

Table 1. Possible Alternative Solar Cells Information Comparison

Solar Cells	Efficiency	V_{oc} (mA/cm^2)	J_{sc} (mA/cm^2)	Year	Ref
c-Si	26.3%	725	42.5	2016	[6]
CIGS	23.3%	734	39.60	2019	[3]
CdTe	22.10%	887	31.69	2016	[3]
III–V//Si (Multi-Junction)	33.3% (Lab data)	-	-	2018	[12]
Perovskite tandem	28%	1800	19.8	2017	[13]

The burgeoning interest in tandem perovskite solar cells, particularly when integrated with silicon, marks an intriguing direction for future research. However, the viability of perovskite tandems is somewhat shadowed by their abbreviated life cycle. Delving deeper, the comparative study on the efficiencies of 2-terminal and 4-terminal tandem solar cells, with a perovskite top layer and silicon base, presents nuanced insights. The 2-terminal configuration, although theoretically poised to achieve efficiencies approaching 35%, is hamstrung by real-world challenges, notably the restricted diffusion length of perovskite cells [11].

In the realm of thin-film PV modules, despite notable advancements and burgeoning academic attention, challenges persist. Their struggle to compete directly with established bulk silicon PV modules is evident. This contention is palpably demonstrated by industry stalwarts like First Solar, which have ventured beyond mere manufacturing. Yet, opportunities beckon in niche sectors, such as Building Integrated Photovoltaics (BIPV). The proliferation of academic discourse and reported advancements in device efficiency doesn't invariably equate to real-world commercial triumphs. This is lucidly exemplified by the surge in interest around “nano technology” and Carbon Nano Tubes (CNTs). Their envisioned role as silicon CMOS replacements was stymied by pervasive manufacturing impediments. The essence of the study is clear: academic prowess must be complemented by pragmatic manufacturing considerations for genuine commercial success. Perovskite cells, in their standalone avatar, grapple with constraints. Their tandem configurations with silicon underscore a need for innovative perovskite materials, given the overlapping absorption properties of both. The paper's advocacy for a four-terminal setup, as opposed to the two-terminal design, signifies the quest for optimized energy extraction. A pivotal aspect underlined is the longevity of perovskite cells. They need to align with the lifespan of silicon cells to emerge as genuine tandem partners. The prevailing challenges and the necessity for meticulous manufacturing strategies render a clear verdict: perovskite cells have a rigorous journey ahead before they can carve a niche in the photovoltaics market [11].

5. Conclusion

PSCs hold substantial promise due to their sustainability and potential cost reductions, positioning them as a potentially transformative technology in solar energy. They are envisaged as an accelerating force in commercial solar applications due to their advantageous properties. However, inherent instability remains a considerable challenge, necessitating continuous refinements compared to the established reliability of silicon-based cells. In parallel, second-generation solar cells, notably those utilizing Gallium, have garnered interest due to their high efficiency and versatility, making them vital contributors to renewable energy. But their potential environmental and toxicological impacts require stringent regulation and management to prevent any harmful consequences. Moreover, tandem solar cells offer noteworthy value, but their integration with silicon structures and stability poses significant challenges. The instability of perovskites compared to the robustness of silicon could affect the resilience and economic viability of the end products. Nevertheless, utilizing four-terminal perovskite tandem silicon solar cells may present viable solutions to current technological constraints. In pursuit of overcoming the limitations of silicon and mitigating environmental concerns related to solar cells, refining and maturing PSCs and other associated technologies is crucial. The overcoming of challenges faced by PSCs could establish them as a formidable alternative. The ongoing advancements in these domains signal a future where solar energy is more efficient and environmentally friendly.

References

[1] Almosni S., Material challenges for solar cells in the twenty-first century: Directions in emerging technologies, Science and Technology of Advanced Materials, 2018, 19 (1): 336 – 369.

[2] Andreani L.C., Silicon Solar Cells: Toward the efficiency limits, Advances in Physics: X, 2018, 4 (1): 1548305.

[3] Efaz E.T., et al., A review of primary technologies of thin-film solar cells', Engineering Research Express, 2021, 3 (3): 032001.

[4] Bosio A., Rosa G., Romeo N., Past, present and future of the thin film CdTe/Cds solar cells, Solar Energy, 2018, 175: 31 – 43.

[5] Iea I., Executive summary–solar PV global supply chains–analysis, IEA. 2022, https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary.

[6] Liu J., Review of status developments of high-efficiency crystalline silicon solar cells, Journal of Physics D: Applied Physics, 2018, 51(12): 123001.

[7] Pastuszak J., Węgierek P., Photovoltaic cell generations and current research directions for their development', Materials, 2022, 15 (16): 5542.

[8] Romeo A., Artegiani E., CdTe-based thin film solar cells: Past, present and future', Energies, 2021, 14 (6): 1684.

[9] Akinoglu B.G., Tuncel B., Badescu V., Beyond 3rd generation solar cells and the full spectrum project. recent advances and New Emerging Solar Cells, Sustainable Energy Technologies and Assessments, 2021, 46: 101287.

[10] Zahedi R., Moosavian S.F., Aslani A., Environmental and damage assessment of transparent solar cells compared with first and second generations using the LCA approach, Energy Science &amp, Engineering, 2022, 10 (12): 4640 – 4661.

[11] Asif A. A., Singh R., Alapatt G.F., Technical and Economic Assessment of perovskite solar cells for large scale manufacturing, Journal of Renewable and Sustainable Energy, 2015, 7 (4).

[12] Cariou R., III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration, Nature Energy, 2018, 3 (4): 326 – 333.

[13] Case C., The path to perovskite performance and production (conference presentation, Organic, Hybrid, and Perovskite Photovoltaics XIX [Preprint]. 2018.