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Solar panels and technological solutions

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Thesis abstract

Degree Programme: Bachelor of Engineering, Automation Engineering

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The aim of the thesis was to propose technological solutions for the growing solar panel manufacturing and installation industries. Specifically, it explored innovations that could help a new company in the field stand out in the market.

The thesis explored the current energy demands, the challenges posed by climate change, and the potential of green energy solutions. The viability of solar energy as an alternative to fossil fuels was emphasised, and the current trajectory was presented.

Additionally, the structure of current solar technology was examined. The inner workings of the cells were explained, and the basics of the photovoltaic effect were showcased. The different types of panels, their functionality, and their respective advantages and disadvantages were thoroughly compared. The required related equipment surrounding the panels was explored, and it was studied how it might improve the overall system. Considerations such as location and weather were also discussed.

Three technological solutions were presented, all of which were designed to use microcontrollers. The mechanical and electrical components necessary for building these solutions were listed, along with an explanation of how they will be used. However, as no working prototype was built, all the solutions were speculative. Nevertheless, planning them may help the company to grow in the future.

The thesis was concluded by presenting the solutions. Also, recommendations were given, and future research focuses, and the limitations of some solutions were introduced.

[1] Keywords: solar energy, renewable energy sources, innovations, microcontrollers, programming

SEINÄJOEN AMMATTIKORKEAKOULU

Opinnäytetyön tiivistelmä

Tutkinto-ohjelma: Insinööri (AMK), Automaatiotekniikka

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Opinnäytetyön tavoitteena oli ehdottaa teknologisia ratkaisuja kasvavalle aurinkopaneelien valmistus- ja asennusalalle. Erityisesti innovaatioita tutkittiin, mitkä voisivat auttaa alan uusia yrityksiä erottumaan kasvavilla markkinoilla.

Opinnäytetyössä tutkittiin nykyistä energiantarvetta maailmassa, ilmastonmuutoksen aiheuttamia haasteita ja vihreiden energiaratkaisujen mahdollisuuksia. Lisäksi painotettiin aurinkoenergian kannattavuutta vaihtoehtoisena energianmuotona fossiilisille polttoaineille ja nykyinen kehityssuunta eri energianmuodoille tuotiin esille.

Samalla tarkasteltiin nykyisen aurinkoenergiateknologian rakennetta. Kennojen sisäinen toiminta selitettiin ja aurinkosähkövaikutuksen perusteet esiteltiin. Erilaisia paneelityyppejä, niiden toimivuutta sekä etuja, että haittoja vertailtiin perusteellisesti. Paneelien ympärillä olevia oheislaitteita tutkittiin ja selvitettiin, miten ne voisivat parantaa kokonaisjärjestelmää. Myös sijainnin ja sään kaltaisia tekijöitä paneeleihin selvitettiin.

Kolme teknistä ratkaisua esitettiin, mitkä kaikki oli suunniteltu käyttämään mikro-ohjainta. Näiden ratkaisujen rakentamiseen tarvittavat mekaaniset ja sähköiset komponentit lueteltiin ja selitettiin, miten niitä voitaisiin käyttää. Koska toimivaa prototyyppiä ei kuitenkaan rakennettu, kaikki ratkaisut olivat spekulatiivisia. Niiden suunnittelu voi kuitenkin auttaa yritystä kasvamaan tulevaisuudessa.

Työn päätteeksi ratkaisut esitettiin. Lisäksi annettiin suosituksia ja tulevaisuuden kehityskohteita sekä esiteltiin joidenkin ratkaisujen rajoitukset.

[1] Asiasanat: aurinkoenergia, uusiutuvat energialähteet, innovaatiot, mikro-ohjaimet, ohjelmointi

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Terms and Abbreviations

AC	Alternating current, a type of electrical current in which the direction of electricity switches back and forth at intervals.
BMS	Battery Management system is a technology facilitating safe usage of battery packs.
DC	Directive current is electrical current with a single direction of flow from negative to positive terminals.
GPIO	General-purpose input/output port that handles both incoming and outcoming digital signals.
PID	Proportional-integral-derivate controller is feedback-based control loop mechanism.
PV	Photovoltaic is conversion of light into energy by using semiconducting materials.

1 INTRODUCTION

Rising concerns about climate change, war and economic shifts have created the notion that alternative energy resources are needed (IEA, n.d.). The increasing frequency of extreme weather conditions, such as droughts and floods, showcases the need for a change in how energy is produced. The resource should be easily accessible, environmentally friendly, and produced locally. Wind, hydro and solar power have all been popular green energy options for decades (Wiatros-Motyka et al., 2024, pp. 10–12), but solar power appears to be the most promising one as it can be installed almost anywhere without the need for the massive funding required for wind and hydro power to be economically viable.

However, it is hard to stand out in the current solar market as it is growing rapidly (IRENA, 2019, pp. 19–22). Grenia is a small company based in Kurikka, Finland, which wishes to emerge in the current PV markets. The aim of this thesis is to investigate the possibility of a few technological solutions that might increase the visibility of Grenia in the market.

The thesis aims to provide insight into the basis of solar panels, the current demand for solar energy, and the ways in which global warming has shaped the green energy industries. The study mostly employs research on solar structures and speculative solutions, but with real components and proven theories. The research focuses primarily on programmable solutions, along with the necessary mechanical components. The findings may not be entirely accurate as physical prototypes will not be produced.

The thesis is divided into four chapters. The first chapter reviews current energy needs, global warming, and renewable solutions, including solar energy. The second chapter details the inner workings of solar panels, their structure, and the different types currently on the market. This chapter introduces related equipment, and the considerations associated with solar panels. The third chapter introduces different technological solutions and their benefits. These technological solutions are mostly based on programmable ideas, but the necessary physical components are also highlighted. The fourth and final chapter offers a conclusion and recommendations and defines the steps necessary for turning speculation into reality.

2 DEMAND FOR ENERGY

According to a Forbes article by Rapier (2024), global energy consumption in 2023 was 12.3 exajoules, 63.6% of which (7.8 exajoules) was contributed by fossil fuels. Renewables contributed the remaining 4.5 exajoules. This represented a 2% increase from 2022. Although renewables grew considerably, fossil fuels still dominated as Figure 1 shows. As global energy demand continues to grow faster than the ability of renewables to keep pace, or displace fossil fuels, the situation remains unchanged.

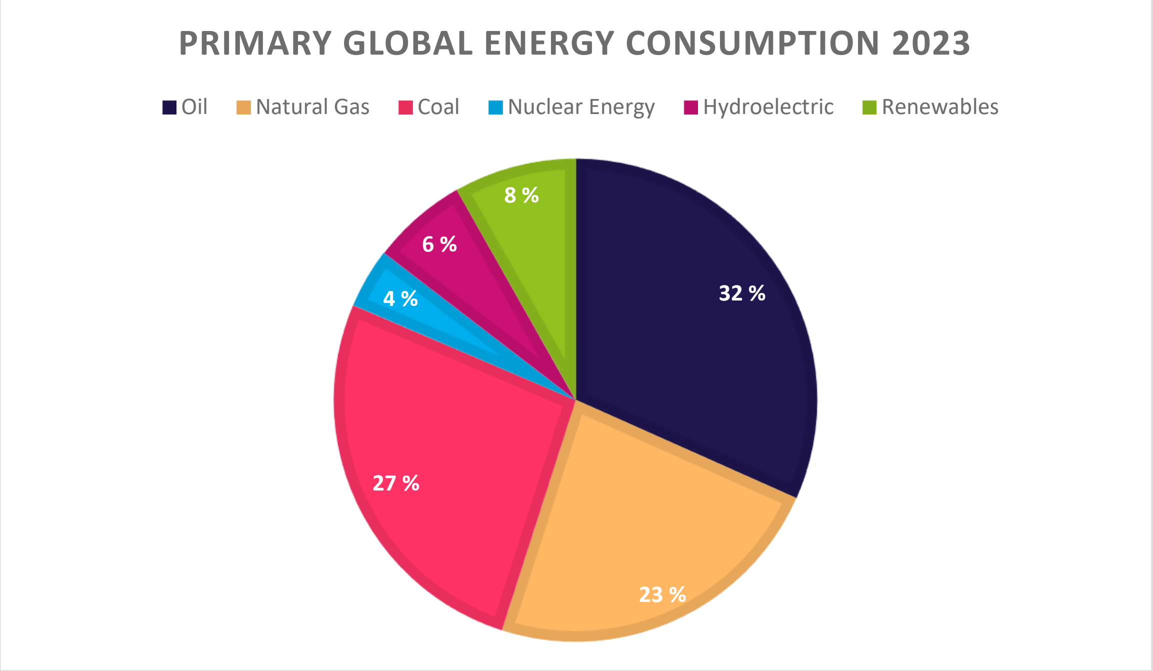


Figure 1. Percentage of different energy sources in 2023 (Rapier, 2024)

According to Statistic Finland (2024), total energy consumption in Finland in 2023 was 1,316,976 tera-joules, of which 29.7% came from fossil fuels and 42.1% from renewables. It is important to note that over half of the renewable energy was produced using wood-based fuels, and hydro- and wind-powered energy dominated the statistics among the green energy sources.

The growth of renewables, especially wind and solar power, has increased notably in recent years (Wiatros-Motyka et al., 2024, pp. 10–12). Of all the renewable energy sources, solar power is spearheading the energy revolution, as it is the fastest-growing source of electricity. In 2023, solar power produced more than twice as much new electricity as coal, and it also made a record in the number of new installations that year. Solar energy production greatly surpassed that of wind and hydro energy, with a global production capacity of 1.6 TW in 2023 (SolarPower Europe, 2024). In comparison, the global energy production capacity of wind power was approximately 1047 GW (WWEA, 2024), while the total capacity of hydro power was around 1416 GW (Statista, 2024).

The global demand for energy is expected to reach 38,127 TWh by 2030 (Wiatros-Motyka et al., 2024, p. 31). In 2022, demand stood at 28,917 TWh. It is predicted that renewables will account for 32% of the global growth in electricity demand by 2030, while fossil fuels will experience a rapid decline of 37%, almost halving the emissions of the energy sector. In the current socio-economic climate, the key question is how to increase energy demand while reducing emissions. A deep and rapid transformation is required if the current economic model is to achieve climate neutrality by 2050 (European Commission, n.d.).

2.1 Global warming and necessity of green energy

According to IRENA (2017, p. 51), limiting the global temperature rise to 2°C would require an energy transition of exceptional scope, depth and speed. The share of energy produced with fossil fuels is expected to fall by more than 70% from the current levels by 2050. The 66% 2°C scenario would require a significant increase in the use of all low-carbon technologies in every country. This ambitious transition would require the gradual replacing of fossil fuels, extensive energy market reforms, and stricter low-carbon and energy efficiency mandates.

Green energy solutions are at the forefront in the fight against global warming that the world is currently experiencing. The threats of acid rain, ozone layer depletion and extreme weather phenomena have led to a situation in which investment in green energy production has become essential (Kalogirou, 2014, pp. 7–11). The war in Ukraine has also shown need for new alternative energy resources in Europe, with the EU reducing its dependency on Russian gas (IEA, n.d.).

Under new policies and market conditions, it is expected that global renewable capacity will increase to 7,300 GW by 2028. Analysis (IEA, n.d.) shows that stronger energy policies could help the EU to achieve its net zero emissions goal by 2050, with renewables such as solar power taking the lead in energy production industries.

2.2 Question about solar energy

Of all the green energy sources, solar energy has experienced the fastest growth. Solar capacity has grown exponentially since the beginning of the century (Wiatros-Motyka et al., 2024, pp. 32–34). From 2000 to 2010, cumulative solar capacity doubled every two years, but from 2010 to 2023, this rate slowed to every three years. Between 2023 and 2030, solar energy capacity is expected to double every 3.8 years. However, this slower pace of growth is not a cause for concern, as the path to tripling global renewables by 2030 does not require exponential growth to continue.

IRENA reports that the cost of solar PV has been decreasing (2022, pp. 24–29). Between 2020 and 2021, the price of utility-scale PV systems dropped by 13%. The reduction in the cost of new PV systems expands the purchasing power of larger projects and makes solar technologies more available to consumers. Manufacturers can produce more units for customers, and technological improvements, such as more efficient PV modules and manufacturing efficiency, which will further reduce commodity prices in the future. However, a similar price drop that was seen between 2020 and 2021 is not expected, and the cost of PV will decrease gradually rather than in spikes.

3 SOLAR TECHNOLOGY

The sun could be thought of as a gigantic fusion reactor that produces 310 EW of energy, 810 PW of which reaches Earth (Klimstra & Hotakainen, 2011, p. 61). This energy is theoretically unlimited for millions of years and could easily meet the current energy demands of humanity. However, it is important to note that the surface of the earth only absorbs 51% of the radiation of the sun (Kortetmäki et al., 2023, p. 38), meaning the most efficient capture of solar energy occurs in space.

Solar energy is primarily captured by solar panels, which are considered the smallest units of a photovoltaic system comprising multiple panels (Adryan et al., 2017, pp. 174–176). The panel serves as a physical module that protects the interwoven solar cells against mechanical damage and moisture. These cells capture and convert sunlight into electricity. When sunlight radiates onto a solar cell, it excites electrons, producing both voltage and current to generate electrical power for consumption.

Ultimately, it is a complicated system comprising multiple parts (Kalogirou, 2014, p. 500). Any new company entering this field should consider all related equipment and the different types of panels and their overall effectiveness. In addition, location, weather and panel management play an important role in the longevity of PV systems (Capehart et al., 2016, pp. 555–557).

3.1 Function of solar cells

Modern solar cells initially require the right material on which the absorption of sunlight raises an electron to a higher energy state (Honsberg & Bowden, 2019). Secondly, the cells require an external load through which the movement of higher energy electrons can dissipate. Electrons then move between the external load and the solar cell, where the excited electrons return and create a circuit. While multiple materials can meet the requirements for photovoltaic energy conversion, almost all conversions use semiconductor materials in a PN junction. The most common semiconductor material used in solar cells is silicon (DoE, n.d.).

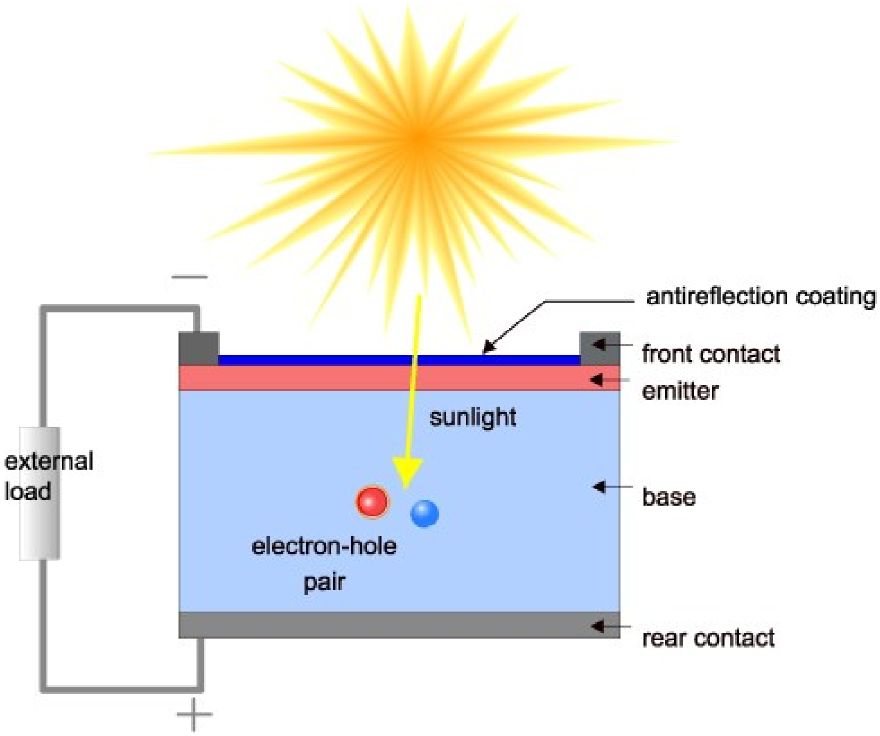


Figure 2. Cross section of the solar cell (Photovoltaics Education Website, 2019).

Solar cells consist of active PV material, metal grids, anti-reflection coating and supporting structures (ASHRAE, 2012, p. 37.19). The design aims to maximize light entry and power output. The active material can consist of various compounds, while metal grids enhance current collection. Anti-reflective coatings optimize light absorption, giving cells a color ranging from black to blue. Each PV cell is a two-terminal device that produces direct current as shown in Figure 2.

3.1.1 PN Junction

The conductivity of materials, such as silicon (Si), which has four valence electrons, can be significantly improved (Peltonen et al., 2018, p. 301). Silicon is doped as an n-type when elements from group V are added, such as phosphorus (P) or arsenic (As), because these elements have five valence electrons. When substituting a silicon atom, the four valence electrons of the group V element form a covalent bond with neighboring silicon atoms, but the fifth electron remains weakly bonded. Once freed, this electron can move around the silicon atom, carrying an electrical current and acting as a carrier.

If silicon is doped with group III elements, which all have three valence electrons (e.g. boron, gallium, or indium), the three valence electrons form covalent bonds with three neighboring silicon atoms. The fourth electron remains unsatisfied, forming an electron hole. This attracts another electron from a neighboring bond, repairing the unsatisfactory bond, and results in the hole moving around the crystal as a charge carrier. This process sustains an electric current, which is useful in electrical circuits.

A PN junction is formed when donor and acceptor atoms are added to a semiconductor (Peltonen et al., 2018, pp. 303–305). These two types of atoms are added to opposite sides of the semiconductor: the donor forms an n-type region (negative), while the acceptor forms a p-type region (positive). The junction is formed at the interface between the p-type and n-type regions, creating a depletion zone within the PN junction.

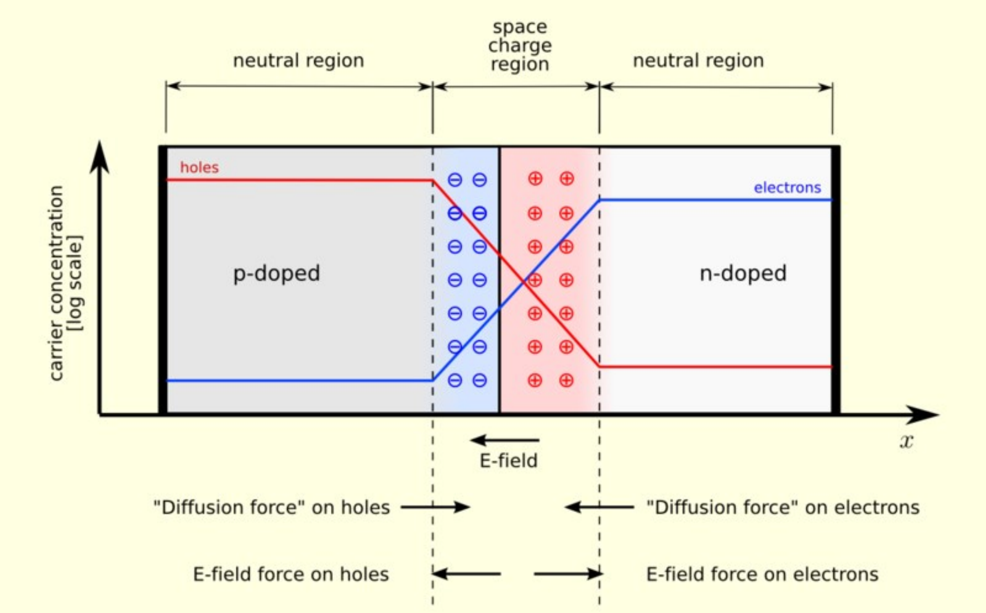


Figure 3. Cross section of typical PN-junction (TheNoise, 2007, CC BY-SA 3.0).

The photovoltaic cells in solar panels consist of p- and n-type semiconductor junctions (Kalogirou, 2014, p. 486). When sunlight strikes a cell, photons generate electron-hole pairs. The electric field then separates these charges, with the electrons moving to the n-type side and the holes moving to the p-type side. Connecting the cell to an external load enables an electric current to flow for as long as sunlight is present as Figure 3 shows.

3.1.2 Photovoltaic effect

PV systems use the photovoltaic effect to convert sunlight into electricity (ASHRAE, 2023). When a photon enters photovoltaic material (e.g. silicon), it can be reflected, absorbed or transmitted. An electron in the valence band of an atom absorbs this photon and its energy increases by the amount of energy in the photon. If the energy of a photon is greater than the band gap of the semiconductor, the electron jumps to the conduction band and becomes free to move. An electric field created by a p-n junction can then remove this electron, generating an electrical current. Without this field, the electron would recombine with the atom. If the energy of a photon is less than the band gap, the electron lacks the necessary energy to jump, converting the excess energy into kinetic energy and raising the temperature. It is important to note that only one electron can be freed per photon, which limits photovoltaic efficiency (Kalogirou, 2014, p. 486).

3.2 Types of solar cells

In the commercial solar cell market, the most used types of cells are monocrystalline or polycrystalline silicon cells (Kortetmäki et al., 2023, p. 40). In thin-film technologies, Amorphous silicon, GIGS and CdTe cells are used for various applications. Various types of third-generation cells are becoming more common. Each material has its own advantages and properties, making them suitable for different solutions in different ways.

Table 1. Properties of common cell types (Kortetmäki et al., 2023, p. 40).

Properties	Polycrystalline	Monocrystalline	Amorphous silicon	CIS/CIGS	CdTe	3rd Gen
Cell efficiency	23,3%	26,8%	14%	23,6%	22,3%	26%
Panel efficiency	20,4%	24,7%	9,8%	20,3%	19,5%	17,9%
Lifespan	Over 30 years	Over 30 years	Over 30 years	Over 30 years	Over 30 years	0,5-3 years
Cost	Moderate	Expensive	Expensive	Expensive	Expensive	Cheap

Table 1 provides an overview of the different cell types. Although the initial cost of each cell type is high, there are differences (Kortetmäki et al., 2023, p. 40). Amorphous silicon, CIS/CIGS and CdTe cells are generally less expensive than basic polycrystalline or monocrystalline cells. However, the former are more efficient, making them a viable option for widespread use. New third-generation cells are mostly still in the testing phase but show promise for future market use.

3.2.1 Monocrystalline and polycrystalline silicon (First generation)

According to IRENA (2012, pp. 4–6), crystalline silicon is the most common material used in the photovoltaic (PV) industry. Silicon itself is one of the most abundant elements in the crust of the Earth, with an energy band gap of 1.1 eV, which makes it a suitable semiconductor. Wafer-based c-Si cells dominate the current PV market as they are easy for individual companies to mass produce and they are also efficient, with the efficiency of 26.8% (Kortetmäki et al., p. 41). The manufacturing process comprises four steps:

1. Silicon production
2. Wafer production
3. Cell production
4. Module assembly.

Waste materials from monocrystalline silicon production can be used in the production of polycrystalline silicon (Kortetmäki et al., 2023, pp. 41–42). The collected waste is melted and formed into the desired shape. This process causes damage to the crystal structure, and therefore the material is called polycrystalline. Although these damages are minuscule, they still affect the energy efficiency of the cell as they can block the path of electrons.

3.2.2 Thin film (Second generation)

Unlike mono- and polycrystalline cells, the silicon atoms in amorphous silicon (a-Si) are arranged in a thin layer (Kalogirou, 2014, pp. 498–499). Amorphous silicon absorbs light more effectively than crystalline silicon, resulting in thinner cells and ultimately giving rise to the term "thin film photovoltaics". The most notable advantages of these cells are their low manufacturing costs, higher energy production per power capacity (kWh/kWp), flexibility and lower weight.

However, amorphous silicon modules have an efficiency of only 14% (Kortetmäki et al., 2023, p. 41), which limits their competitiveness in the market. However, their low manufacturing costs enable them to be used in a wide variety of applications. Despite these benefits, they face increasing competition from other thin-film technologies that offer higher efficiencies.

CIGS (copper indium gallium selenide) is one of the three most common thin-film technologies, alongside a-Si and CdTe (cadmium telluride) (IRENA, 2012, pp. 5–6). Like amorphous silicon, CIGS layers can be produced in thin layers for use in bendable solar panels. Unlike a-Si cells, CIGS cells are more efficient: according to Kortetmäki et al. (2023, p. 42), their peak efficiency in a laboratory environment was 23.6%. Their good efficiency, low cost and light weight make CIGS ideal for rooftop installation, in both residential and commercial settings.

Cadmium telluride (CdTe) cells are mostly used in utility-scale solar power plants (Kalogirou, 2014, p. 499). Like the previously mentioned thin film cells, they are a light and low-cost option for consumers. Their efficiency is around 22.3% (Kortetmäki et al., 2023, p.

41), which is higher than amorphous silicon cells, but lower than CIGS and crystalline silicon cells. However, it is important to note that tellurium is toxic and difficult to recycle, which could make it an unattractive option for consumers.

3.2.3 Third generation

Alternatively, new third-generation panel technologies have emerged on the market (Kortetmäki et al., 2023, p. 43). These include concentrating photovoltaic (CPV) cells, perovskite solar cells (PSCs), dye-sensitized solar cells (DSSCs) and organic solar cells (OPVs), as well as other novel solar cell concepts, such as quantum dot solar cells (QDSCs).

A concentrating photovoltaic (CPV) system uses optical devices such as lenses or mirrors to focus direct solar radiation onto small, highly efficient multi-junction solar cells produced from semiconductor materials (IRENA, 2012, pp. 6–7). The concentration factor of sunlight in these systems can range from 2 to 100 suns for low-to-medium concentration systems. In some systems, this can be as high as 1000 suns for high-concentration systems.

CPV systems can achieve module efficiencies of up to 40% and system efficiencies of around 25% (Kalogirou, 2014, pp. 529–531). The addition of a solar tracking system enables CPV to start generating energy earlier in the morning and continue later in the evening, thus maximizing overall energy production. However, the high concentration of sunlight can overheat the cells, reducing efficiency or causing damage. The system requires direct sunlight to function, making it unsuitable for cloudy areas. CPV systems showed great potential, but have been in decline since 2012, as can be seen in Figure 4.

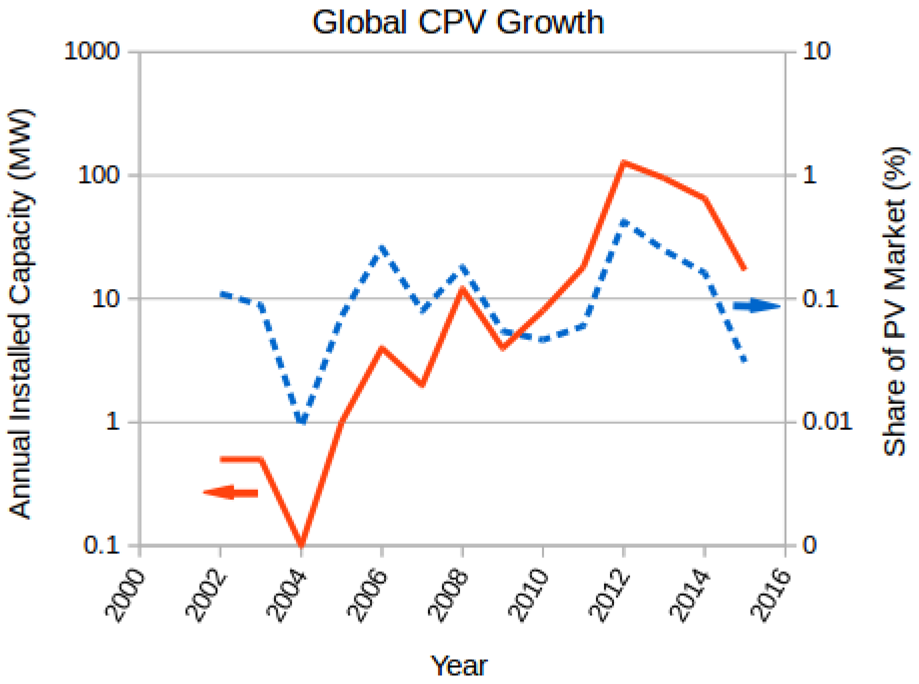


Figure 4. Global CPV Growth between 2002 and 2015 (Bikesrcool, 2018, CC BY-SA 4.0).

Different types of perovskite solar cell have displayed high performance capabilities and low production costs (Kortetmäki et al., 2023, p. 43). Cell materials currently in development are either based solely on perovskite minerals, or perovskite has been added to silicon or CIGS cells to improve their energy efficiency.

The main benefit of perovskite is that it can respond to different wavelengths, making up for the limitations of other cell materials. An example of this is the tandem cell, a perovskite-silicon combination that achieved an efficiency of 33% under laboratory conditions. The highest efficiency achieved with a perovskite cell alone is 26% (Kortetmäki et al., 2023, p. 41).

While perovskite has become highly efficient, there are still some challenges to address before it can compete in the market (Kortetmäki et al., 2023, p. 43). Notable challenges include overall costs, cheaper cells, shorter lifespans, damage from moisture, enlargement of laboratory products, toxicity, and recycling.

A dye-sensitized solar cell (DSSC) is a type of photoelectrochemical cell that combines semiconductor structures formed between a photosensitized anode and an electrolyte (IRENA, 2012, p. 7). These cells are unique among solar technologies as they aim to mimic the natural process of photosynthesis and lack the PN junction found in most solar cell types.

DSSC cells can be colored differently and made in various shapes, or even be colorless (Kortetmäki et al., 2023, p. 43). They are cheaper to produce than silicon-based cells and do not contain any toxic materials, making them safe for humans and the environment.

The photo-sensitive anode of a DSSC cell is made from titanium dioxide (TiO_2), which acts as the semiconductor of the cell (IRENA, 2012, p. 7). Dye molecules absorb sunlight and facilitate charge separation, thus generating photocurrent. A liquid provides charge transport for electrolytes, but its nature can be problematic, especially in freezing conditions. The basic operation of a DSSC cell occurs when photons hit the dye, exciting electrons which are then released from the TiO_2, creating an electric current.

DSSCs offer a simple, low-cost solution, making them ideal for large-scale production. However, in laboratory conditions, its peak efficiency has been found to be only 13% (Kortetmäki et al., 2023, p. 43). A significant limitation of DSSCs is the lack of dyes that can absorb a broad range of the solar spectrum.

Organic solar cells (OPVs) are produced from organic or polymer materials, such as polymers and small organic molecules (IRENA, 2012, pp. 7–8). There are several types of material used in organic solar cells, which have one or more layers of different absorptive materials between the metals and the electrolytes. The advantages of organic solar cells include their light weight and flexibility, making them ideal for portable applications. They can potentially be integrated with various surfaces or incorporated into housing.

Recently, the efficiency of organic solar cells has increased to 19.2% (Kortetmäki et al., 2023, p. 43), and research into the cells focuses on increasing efficiency and extending lifespan.

A quantum dot solar cell (QDSC) is a solar cell that uses quantum dots as an absorptive material (Kortetmäki et al., 2023, p. 44). They can replace heavier materials such as silicon or copper-indium-gallium-selenide (CIGS). Large-scale production of QDSCs could be achieved using spray or roller printing systems, reducing the cost of manufacturing the panels and, in turn, their price. A major benefit of these panels is that their band gap can be adjusted without altering the underlying material, enabling optimization for different wavelengths and repurpose of energy. In laboratory tests, the energy efficiency of QDSCs peaked at 18.1%.

3.3 Related equipment

To function properly, the PV system requires related equipment (Kalogirou, 2014, p. 500). This includes batteries, battery charge controllers, inverters and peak-power trackers, for example. PV modules can last for many years, so the supporting structures, components and buildings should be designed to last at least as long, if not even longer.

3.3.1 Batteries

In some PV systems, batteries are essential for providing power at night or during periods of low solar output (ASHRAE, 2012, p. 37.21). The type and size of battery required depends on the specific load and availability requirements, and they should ideally be stored in a temperature-controlled environment (between 10 and 24°C) with proper ventilation. Common battery types include lead-acid, nickel cadmium, nickel hydride and lithium batteries. Of these, deep cycle lead-acid batteries are widely used due to their ability to handle repeated deep discharges. Batteries can be flooded or valve regulated. While requiring greater maintenance, flooded or wet batteries can last longer with proper care. Valve-regulated batteries require less maintenance.

Batteries can be arranged in parallel or in series. However, it is important to note that using more than three strings in parallel may result in uneven performance, failure of some batteries or, worse yet, the need to replace the entire battery bank (ASHRAE, 2012, p. 37.21).

3.3.2 Charge controllers

In PV systems, battery charge controllers regulate the flow of electricity from PV modules to batteries (Kalogirou, 2014, p. 503). They are crucial in preventing both overcharging and over discharging of batteries. These controllers can be classified as either shunt or series types, and some include a low voltage disconnect feature. Most controllers operate under two main conditions. The first is the normal charging condition, in which the battery voltage fluctuates between acceptable maximum and minimum values. The second condition is Over-Charge or Over-Discharge, which occurs when the battery voltage reaches a critical threshold. In this mode, a switch, either electromechanical or solid-state, uses a hysteresis cycle to manage operations.

The charging process with the controller typically involves four phases (ASHRAE, 2012, p. 37.21).

- The bulk phase, in which the battery is charged to around 85% of its capacity.
- The absorption phase maintains voltage while regulating current.
- The float phase keeps the battery slightly above its resting voltage.
- Lastly, the equalization phase involves intentionally overcharging the battery to ensure electrolyte distribution and maintain its health.

Some controllers can optimize the operating voltage of PV modules independently of the battery voltage to maximize power output. This is called peak power tracking and involves continuously adjusting the voltage based on output wattage sampled multiple times per second. Peak power trackers can be standalone devices or integrated into charge controllers and inverters.

3.3.3 Inverters

Inverters convert the direct current (DC) produced by photovoltaic (PV) systems into the alternating current (AC) typically used by household appliances and the power grid (Kortetmäki et al., 2023, pp. 70–71). They can output single-phase or multiphase power at various voltages and frequencies, but in Finland this is typically 230 V AC at 50 Hz. Since most major appliances use AC power, the DC electricity produced by solar panels cannot be used without an inverter.

Most inverters can now be categorized according to their interaction with the grid (ASHRAE, 2020, p. 37.21). In large- to medium-scale plants, every panel may be connected to a single central inverter. String inverters connect a set of panels, or "string", to a single inverter (DoE, n.d.). Microinverters are smaller inverters placed on each panel, so shading or damaging to one panel does not affect the power that can be drawn from the others. However, this system is usually more expensive as each panel requires an inverter.

According to Kortetmäki et al. (2023, p. 74), off-grid or hybrid inverter capabilities are usually more flexible than on-grid capabilities. In on-grid systems, solar panels can power the local grid directly through the inverter. This is a straightforward and cost-effective solution, but it can be prone to blackouts if the panels are not producing enough energy. Off-grid systems can operate independently from the general electrical grid, making them suitable for remote areas. These systems incorporate storage solutions, most often in the form of batteries, to store excess electricity generated by the panels. This ensures continuous power supply on days when there is insufficient solar energy.

3.3.4 Maximum power point tracker

The maximum power point tracking (MPPT) controller plays a critical role in PV systems (ASHRAE, 2020, p. 37.21) by optimizing the output of solar panels in all weather conditions. This is achieved through continuous monitoring of voltage and current to ensure the panels always operate at their most efficient voltage. Most off-the-shelf inverters and charge controllers today are integrated with MPPT technology. The controller uses an algorithm to determine the maximum power point or peak power voltage. The maximum power varies with solar radiation, with a typical maximum power voltage of around 17 V when the measured cell temperature is 25 °C. This can drop to around 15 V on a hot day or rise to 18 V on a cold day (LEONICS, n.d.).

The main principle of MPPT is to extract the maximum available power from PV modules by operating them at their maximum power point, also known as the most efficient voltage (LEONICS, n.d.). The MPPT monitors the output of the PV module and compares it to the battery voltage. It then adjusts the power output of the PV module to charge the battery and converts it to the optimal voltage to maximize the current supplied to the battery. MPPT is most effective in cold weather and on cloudy or hazy days. Typically, PV modules also perform optimally at low temperatures.

3.4 Considerations

PV cells are highly reliable, as they were first used in space, where repairs were difficult or impossible (Capehart et al., 2016, pp. 555–557). Their low operating costs and modularity make them ideal for widespread use. In the current climate, they have become a necessity in the fight against climate change. However, they still have disadvantages that need to be addressed. PV cells only produce DC power, which is a limiting form of energy suitable for certain applications only. PV systems require at least an inverter as related equipment if the energy required is in the form of AC. Conversion from DC to AC can generate undesirable harmonics that need to be filtered or otherwise controlled. Although PV systems are considered cheap to construct, location, weather and technology play a major role in the potential investment needed for the system.

3.4.1 Location

Although solar energy collection is efficient, it is volatile due to the constant changes in cloud cover and the position of the sun (Milano, 2022, p. 157). The best location for the panels is a wide, flat area without any objects that may cause shading (Spiegel, 2019). Before any projects begin, the site should be surveyed to collect information on how the times of day and seasons affect shading of the PV panels, the optimal location of the panels, and how they interface with the existing electrical system. Shading is most often caused by trees, buildings, power lines or even other parts of the array.

Plotting the path of the sun helps to conduct shading evaluations (Spiegel, 2019). The altitude and azimuth angles of a shading object can be measured from the panel location and plotted on a sun position chart for a specific latitude. In some systems, one row of panels can shade another if the rows are closely spaced. Even shading tens of centimeters can affect the energy collection of another row.

3.4.2 Weather

Weather plays a significant role in the functioning of solar panels (Ilum Solar, n.d.). An increase in temperature negatively affects the voltage and current of the panels, reducing the amount of energy they produce. This is due to an increase in resistance at higher temperatures; therefore, the optimal location for solar panels is in cooler climates. It is estimated that the most efficient temperature for solar panels is around 25°C.

Humidity and high winds can damage the panels (SunPower, n.d.). Humidity can cause rust and mold to form on the panels, reducing their overall efficiency. While a light breeze can help cool the panels in hot weather, strong winds, especially gusts, can damage the panel structure. While most modern panel structures can withstand wind speeds of up to 62.58 m/s, problems may arise with moving structures such as solar tracking systems. In colder climates, snow can damage the panels when it accumulates on top of them. Snow greatly reduces sunlight exposure and the overall energy output of the panels. Snow also adds stress and weight to the panel structure, and too much weight could cause the panels to collapse. It is estimated that 50 kg of snow accumulates per cupid meter (NASA, n.d.).

4 TECHNOLOGICAL SOLUTIONS

The solar system market is growing faster than ever before, largely due to rising concerns about climate change (IRENA, 2019, pp. 19–22). This has made entry into the market more difficult, especially for companies without extensive experience. Therefore, technological solutions should be considered to ease this transition to the solar market. These include solar tracking systems, battery management systems (BMS) and remote monitoring of the panels, for example.

4.1 Solar tracking

Using a servo or stepper motor, a microcontroller and sensors, it is possible to track the location of the sun in the sky using a PID controller (Priyadarshi et al., 2022, p. 290). This process can maximize overall energy production by guiding the panels to the optimal position based on the location of the sun and maintaining an optimal tilt angle.

Solar tracking can be categorized into three systems (ASHRAE, 2012, p. 37.21). The simplest of these is a single-axis tracker, which follows the position of the sun from east to west with the panel tilted at a fixed angle. A dual-axis tracker follows the sun from east to west as in a single-axis system but can also adjust the tilt angle of the panel north and south according to the elevation of the sun in the sky. An azimuth tracker has a fixed slope and rotates around a vertical axis. Proper usage of these systems can increase solar energy harvest by approximately 30% or more.

Solar trackers, especially dual-axis and azimuth trackers, can be subdivided into open-loop or closed-loop control systems (Priyadarshi et al., 2022, pp. 291–292). An open-loop system uses an algorithm to determine the location of the sun in the sky. The exact position of the sun can be determined from its relative position to the solar module by measuring the relationship between the sun and the Earth at any given location. This algorithm is loaded into the processor that controls the tracker, and accurate outcomes are assessed by including date and time information.

Closed-loop control systems are more common than open-loop systems (Priyadarshi et al., 2022, p. 292). Sun tracking is done by a sensor rather than an algorithm. This control system is more effective for solar tracking, but it has some significant drawbacks. The feedback signal creates noise in the system, which affects stability. Additionally, the tracking sensor incurs extra costs for the system and consumes more energy than the open-loop algorithm.

4.1.1 Mechanical structure

A functional solar tracking system requires a mechanical structure, including an electrical motor, panels, a frame and a gearbox for the motor (Lin Engineering, n.d.). Electrical enclosure is also necessary to house and protect the electrical components. As the system is intended for outdoor use, an ingress protection rating of IP65 is recommended (Omron, n.d.). Additionally, it is highly recommended that the frame includes a locking or braking mechanism to prevent the panels from moving in strong winds and damaging the system (Schletter Group, n.d.).

Table 2. Differences of servo- and stepper motor (AMCI, n.d).

Properties	Servo motor	Stepper motor
Design	Closed-loop design	Simple design
Control	More complex control, tuning required	Smooth control at low speeds
Torque	Better torque control in various speeds	Torque decreases in high speeds
Load	Better choice for variable load systems	Cannot react to changes of load
Cost	Higher overall cost	Lower overall cost

Of these motors listed in Table 2, the servo motor is clearly the superior option, despite the drawbacks of higher cost and complexity (AMCI, n.d.). The torque control is superior, especially at various speeds, and the ability of a motor to handle heavier loads is advantageous, particularly when snow covers the panels and adds extra weight. Although the locking system is integrated into the frame, the servo motor provides an additional safeguard against system malfunction. Nevertheless, the simpler design of stepper motors brings considerable competition. The cost is lower, and the ability of the motor to provide smoother control at lower speeds is notable, considering how slowly the panels will move according to the position of the sun as the rotation of the earth maintains a similar location in relation to the sun. With a built-in locking system to protect the structure, the servo ability of a motor to handle high winds can be marginal, making no difference between a servo motor and a stepper motor. Freshly fallen snow is considered light weighing only 50 kg/m³, so it should be expected that the panels would not operate properly in deep winter (NASA, n.d.).

Multiple electrical motors are available with gearboxes (Lin Engineering, n.d.). The typical ratios are 5:1, 10:1, 50:1 and 100:1. Almost all gearboxes for motors are planetary in nature but differ in terms of precision and capabilities. Usually, stepper motors have a wide variety of gearboxes, whereas servo motors do not. This factor can play an important role in deciding which motor type should be chosen.

The weight of the panels plays a crucial role in choosing the right motor and gearbox ratio. Monocrystalline panels of similar size rarely differ in weight. For example, the JA Solar JAM60S20-390/MR weighs 20.2 kg (Merxu, n.d.). The dimensions of the panel are 1769 x 1052 x 30 mm, with the maximum energy output of 390 W, making it a standard choice for solar applications.

Larger panels could also be considered for the system, such as the Trina Solar TSM-DE17M(II) 500 W monocrystalline panel (Trina, 2020). This panel is heavier weighing 24 kg, and it has dimensions of 2102 x 1040 x 35 mm. The maximum energy output of this panel is 500 W, and it could be considered for larger systems comprising multiple panels.

Solar tracking systems can have one or multiple panels, but multiple panels are recommended as they produce a better energy output with lower operating costs (Schletter Group, n.d.). Neither an electrical motor nor a servo or stepper motor can move the panels on their own; thus, they require a gearbox to maximize the torque.

First, the necessary torque required to move the panels must be calculated using the formula (NASA, n.d.):

$$F = m \, x \, g \, x \, r \tag{1}$$

where

F is the torque required for the panels to move

m is the mass of the panels and necessary equipment

g is the gravitation of the earth acting on the mass

r is the distance from the axis of rotation where the force is applied.

For example, if the weight of the panels and equipment is 100 kg, the acceleration due to gravity is 9.81 m/s² and the distance from the axis is 1 m, the required torque can be calculated using formula (1):

$$F = 100\ kg\ x\ 9{,}81\ m/s2\ x\ 1\ m\ =\ 981\ Nm$$

If the nominal torque of an electrical motor is 30 Nm and it is fitted with a 35:1 ratio gearbox, its torque can be increased to 1050 Nm, which is more than enough to move a 100 kg panel system.

NEMA 34 stepper motor can be used for lighter builds, such as a single-axis tracker with two JAM60S20-390/MR panels (Joy-IT, n.d.). The torque of the motor is 11 Nm and, since each panel weighs 20.2 kg, the initial weight of the system is 40.4 kg, excluding additional equipment. The torque required for the panels to move can be calculated using the following formula (1):

$$F\ =\ 40{,}4\ kg\ x\ 9{,}81\ m/s2\ x\ 1\ m\ =\ 396\ Nm$$

The torque required for the panels is 396 Nm. To ensure the tracking system functions properly, a gearbox with a 50:1 ratio should be used, increasing the total torque to 550 Nm. Considering the size of Grenia, using a solar tracking system with these mechanical components is a viable, cost-effective solution.

4.1.2 Control system

A microcontroller is a single-chip integrated circuit (IC) in an embedded system that performs a particular operation (Varsha, 2022, p. 228). They contain a processor and memory unit, as well as input and output ports. Microcontrollers are used in various industries worldwide (Sharma et al., 2022, p. 85). Their small size, programmability and efficiency make them useful for measuring quantities, temperatures and voltages, and for controlling certain applications, such as solar trackers.

The program executed inside the microcontroller is usually stored permanently in non-volatile memory (Schäuffele & Zurawka, 2016, p. 56). This means that the program cannot be exchanged or modified to handle different applications. An exception occurs when a new software version is downloaded and programmed into Flash memory as part of a software update.

In terms of programming, it would be possible to start with a simplified microcontroller (Schäuffele & Zurawka, 2016, p. 57). The microprocessor comprises the programmable entity that handles and manipulates the data. The processor also controls the time-specific and logical execution of a program implemented in the memory of the controller.

Various memory areas are used for storing data and introducing programs (Schäuffele & Zurawka, 2016, p. 57). Variable memory requires read access memory (RAM). Read-only memory (ROM) is used for tasks such as program introduction and permanent data storage. Most modern controllers contain additional integrated memory modules and registers to provide rapid read and write access.

Table 3. Main differences between microcontrollers (Velasco, 2023).

Microcontroller	Applications
Atmel ATMEGA328P	Flexible on smaller projects, but lacks the computing power
Raspberry Pi	High processing power with flexibility in different uses
ESP32	Simple, cost-effective solution with good computing power

The three most popular microcontrollers shown on Table 3 are the Raspberry Pi, the ESP32 and the Atmel ATMEGA328P, the latter of which is usually used in the Arduino Uno microcontroller boards (Velasco, 2023). While they can all be implemented in a solar tracking system, there are some small variations. The Atmel is a good, inexpensive controller, but its lack of computing power that may hinder the operation of the system. However, if the system is small, Atmel would be a great option, as it is often used in small projects. Like Atmel, the ESP32 is a simple, cost-effective option, but it has much better computing power. Of these options, the Raspberry Pi is the best solar tracking solution as it has high processing power and can be used for various projects. Its architecture is also hugely different from that of the other two options (Raspberry Pi, 2025). The Raspberry Pi is a small computer that can run full-featured operating systems, such as Linux. This makes it useful for large-scale applications.

The Raspberry Pi 5 is the newest model in the microcontroller series (Raspberry Pi, 2025). It houses 40 GPIO pin heads, two USB 3.0 ports, two USB 2.0 ports and a single Gigabit Ethernet port. Alongside the Ethernet cable, it has dual-band 802.11ac Wi-Fi as an alternative option for connecting to the internet. The RAM can be up to 16 GB in the high-end variants, making it a powerful and flexible choice for extensive applications.

The microcontroller can be connected directly to motors via the GPIO pins (Raspberry Pi, n.d.). The Raspberry Pi can control up to six electrical motors but is only suited to smaller systems due to the limited number of pins, and the real-time reference is not accurate with this configuration.

As the Raspberry Pi supports the Python library, it is possible to use the RS-485 Modbus and the Python PyModbus library to control the functions of electrical motors (PyModbus, 2025). This involves connecting one or two UART interfaces to multiple motor controllers via the RS-485 (Peňa & Legaspi, 2020). Modbus protocols allow multiple devices to be connected, enabling control of several motor drives on a single bus. This is a much friendlier option for industrial conditions, such as interference and long cable runs of up to 1200 metres (Zhang, 2010, p. 583). It also allows for versatility in the event of the future integration or expansion of various devices.

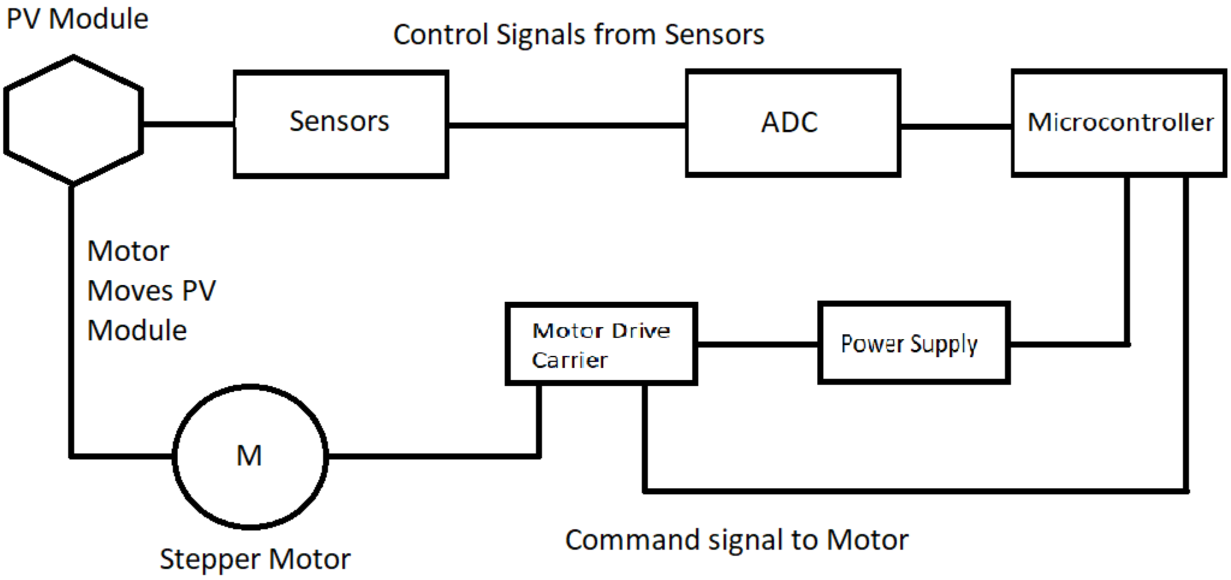


Figure 5. Simple layout for the tracker.

Additionally, the control system requires light-dependent resistors (LDRs), which are light-sensitive sensors most often used to indicate the presence or absence of light (EEPower, n.d.). These are a necessary component of closed-loop designs which is presented in Figure 5. The system requires at least two sensors so that the panels can track the sun. The LDR sensors search for the light source with the highest level of infrared light.

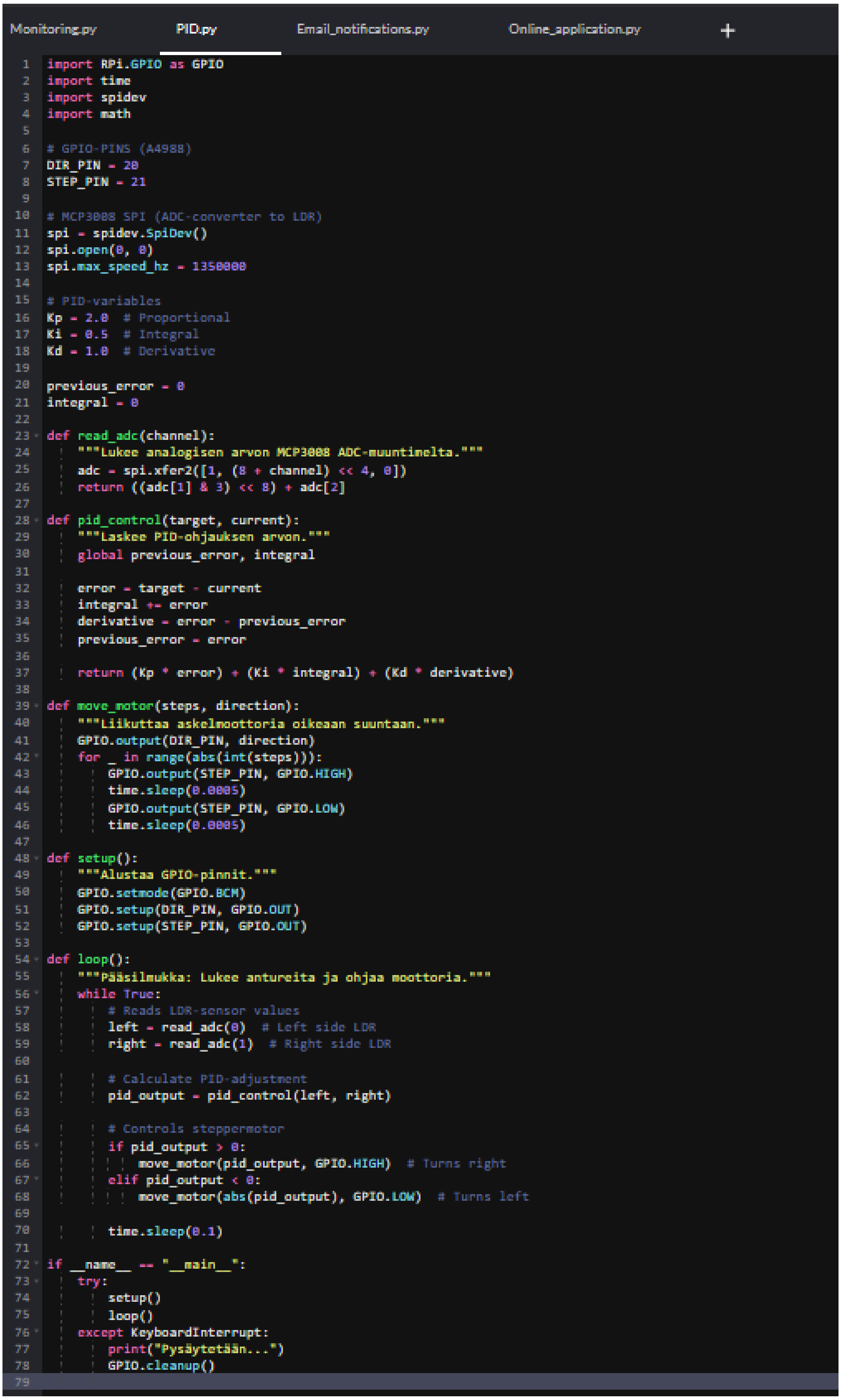
As the signal type from an LDR is often analogue, it cannot be used in the program and an analogue-to-digital converter is needed (EEPower, n.d.). The MCP3008 8-channel 10-bit ADC (analogue-to-digital converter) is a cost-effective choice for converting analogue signals from LDRs to digital, making them usable in the programme and enabling tracking of the movement of the sun (Rembor, 2018).

While not essential, it is highly recommended to have a motor driver carrier to control stepper motors via GPIO pins from the microcontroller (Lentin, 2018, p. 109). Having a motor driver carrier provides better control of the motors, such as managing speed or voltage. Elecrow A4988 stepper motor driver module is an excellent choice for use in a solar tracking system (Elecrow, n.d.). It would be installed next to the microcontroller and connected to its GPIO pins, with electrical cables continuing to the motors.

4.1.3 Program for the tracker

The solar tracking system program was developed using Python, as this comes pre-installed on Raspbian devices (Schooneveld, 2020).

Some form of feedback control is needed for the program, as errors are likely to occur. This involves taking corrective actions based on evaluations of the situation. If the situation remains unsatisfactory and an error occurs, further action will be taken (Wade, 2017, pp. 83–86). The PID controller is probably the most widely used feedback control mechanism, combining three control modes: Proportional (P), Integral (I) and Derivative (D). These controllers are used in various industrial processes, including temperature control, flow regulation and pressure management. Proportional control adjusts the current output proportionally to the error. Integral (I) accounts for the accumulation of past errors, helping to eliminate the offset by adjusting the output based on the sum of errors over time. Derivative (D) predicts future errors based on the rate of change, which helps dampen the response of the system and improve stability. PID controllers present additional parameters in the form of tuning: Kp for proportional, Ki for integral and Kd for derivative. These parameters are crucial for optimal performance and can vary greatly depending on the application.



```python
import RPi.GPIO as GPIO
import time
import spidev
import math

# GPIO-PINS (A4988)
DIR_PIN = 20
STEP_PIN = 21

# MCP3008 SPI (ADC-converter to LDR)
spi = spidev.SpiDev()
spi.open(0, 0)
spi.max_speed_hz = 1350000

# PID-variables
Kp = 2.0  # Proportional
Ki = 0.5  # Integral
Kd = 1.0  # Derivative

previous_error = 0
integral = 0

def read_adc(channel):
    """Lukee analogisen arvon MCP3008 ADC-muuntimelta."""
    adc = spi.xfer2([1, (8 + channel) << 4, 0])
    return ((adc[1] & 3) << 8) + adc[2]

def pid_control(target, current):
    """Laskee PID-ohjauksen arvon."""
    global previous_error, integral

    error = target - current
    integral += error
    derivative = error - previous_error
    previous_error = error

    return (Kp * error) + (Ki * integral) + (Kd * derivative)

def move_motor(steps, direction):
    """Liikuttaa askelmoottoria oikeaan suuntaan."""
    GPIO.output(DIR_PIN, direction)
    for _ in range(abs(int(steps))):
        GPIO.output(STEP_PIN, GPIO.HIGH)
        time.sleep(0.0005)
        GPIO.output(STEP_PIN, GPIO.LOW)
        time.sleep(0.0005)

def setup():
    """Alustaa GPIO-pinnit."""
    GPIO.setmode(GPIO.BCM)
    GPIO.setup(DIR_PIN, GPIO.OUT)
    GPIO.setup(STEP_PIN, GPIO.OUT)

def loop():
    """Pääsilmukka: Lukee antureita ja ohjaa moottoria."""
    while True:
        # Reads LDR-sensor values
        left = read_adc(0)  # Left side LDR
        right = read_adc(1)  # Right side LDR

        # Calculate PID-adjustment
        pid_output = pid_control(left, right)

        # Controls steppermotor
        if pid_output > 0:
            move_motor(pid_output, GPIO.HIGH)  # Turns right
        elif pid_output < 0:
            move_motor(abs(pid_output), GPIO.LOW)  # Turns left

        time.sleep(0.1)

if __name__ == "__main__":
    try:
        setup()
        loop()
    except KeyboardInterrupt:
        print("Pysäytetään...")
        GPIO.cleanup()

```

Figure 6. A python code for PID solar tracker.

Figure 6 shows the function of the program. As Python is preinstalled on the microcontroller, the Raspberry Pi GPIO library must be imported into the Python script so that the code can monitor signals from the sensors and control the motors (Raspberry Pi, n.d.). The time library is also imported, as it is typically used for delays or timing-related tasks. The GPIO pins DIR_PIN and STEP_PIN are used to set the direction of the stepper motor and to send signals to it. Both pins are configured as outputs.

The Spidev library provides the interface functions for communicating with SPI devices such as the MCP3008 ADC, which is installed alongside the microcontroller to read values from two LDRs. Initialising the SPI interface enables communication with the MCP3008 ADC. The program reads an analogue value from the specified channel of the MCP3008 ADC, and this information is then sent digitally to the main loop.

The PID control variables are written into the code, where Kp, Ki and Kd are the constants for the PID control algorithm. Previous_errors stores the last error values for calculating Kd, the derivative. Integral accumulates the error over time for an integral part of the PID algorithm. The PID controls are calculated constantly, based on the target and current values. The PID control system updates the integral and derivative components and, in turn, returns control values to the PID output.

The main loop reads values continuously from two LDRs, calculates the PID output and therefore moves the motor based on the results. If the output is positive, the motor turns right; if the output is negative, the motor turns left. In the “move motor” function, the stepper motor is given a certain number of steps in each direction. The STEP_PIN is toggled to create the stepping motion.

Finally, when the script is run directly, the GPIO pins are set up and the main loop is entered. If interrupted, for example by the CTRL+C key combination, it cleans up all GPIO settings.

4.2 Battery management

A battery management system (BMS) protects and balances the batteries in PV systems (Wang et al., 2022, p. 371). The system detects voltage, current and temperature in real time, as well as leakages, thermal management, battery management and the discharge power capacity of the panels.

The BMS is also useful for protecting the cells of the panels and components that receive energy from the panels (Hu et al., 2021, pp. 128–130). It works by monitoring the voltage, current and temperature of individual cells, as well as the state of charge of the battery pack, in accordance with the energy management algorithm of BMS. There are many implementations of the system, with most BMS systems consisting of slave and master modules. The slave module connects to each cell via sensors that monitor the condition of the cells. They implement cell balancing and communicate with the master module. The master module connects to multiple slave modules and calculates the battery state of charge (SOC). It controls the main battery isolation and initiates battery protection and the thermal management system in response to data from the main voltage, current or temperature inside the slave modules. The module also provides system communications.

There are passive and active cell balancing techniques (Singh et al., 2024, pp. 64–66). In passive balancing, resistors dissipate excess energy from higher voltage cells, thus equalizing voltage or SOC. In active cell balancing, additional circuitry is used to transfer energy between cells, leading to more efficient equalization. This energy dissipation can be used to push energy directly towards the local grid or battery using relays, inverters and charge controllers. It is suggested that energy from solar panels is directed towards the grid via an inverter when the battery load is sufficient and is used to charge the batteries when their levels are low. The local grid can still be fed with power from the batteries when the solar panels are not producing enough power.

4.2.1 Necessary components

The Raspberry Pi is used as a microcontroller for the solar tracking system. It can also be used in a BMS system, not only to control the direction of energy, but also to notify the user whenever energy is directed to the battery or grid. This can be done via email, for example, as the microcontroller can be connected to the internet via either LAN or Wi-Fi (Raspberry Pi, n.d.).

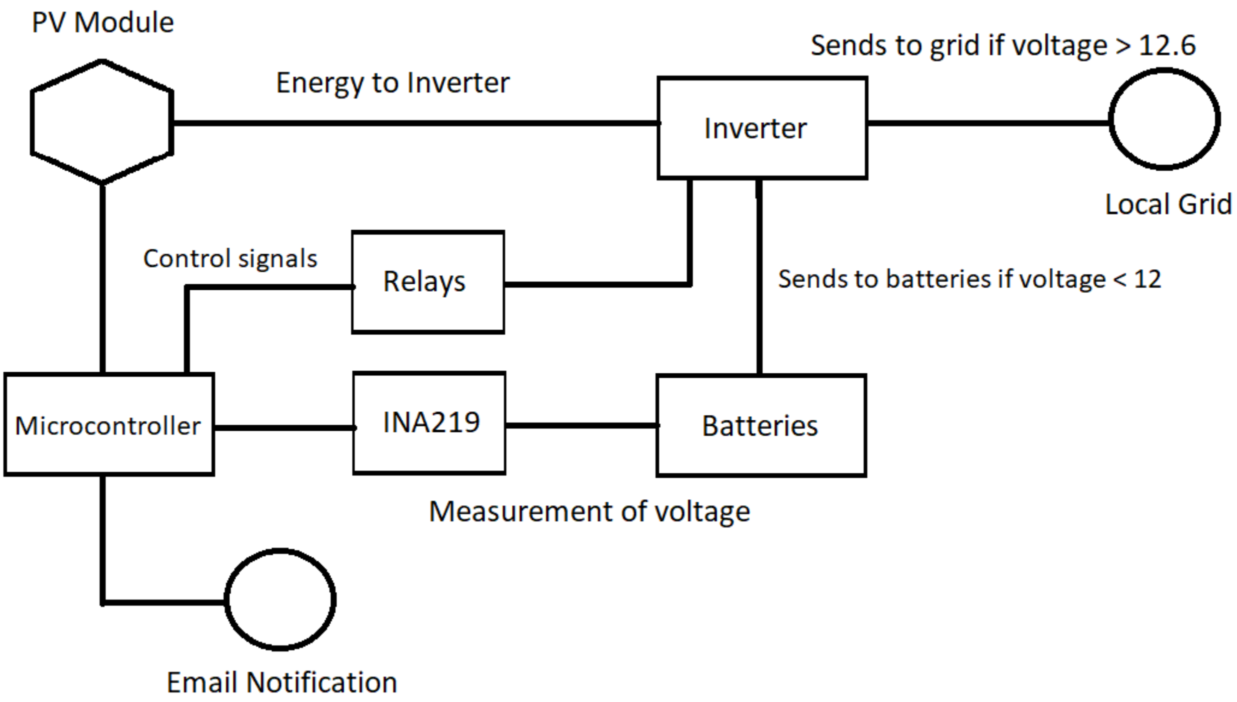


Figure 7. Simple layout of BMS.

Figure 7 shows that a sensor is required for the microcontroller to manage the battery management system. The INA219 is a bidirectional current/power monitor that can sense voltages from 0 to 26 V (Texas Instruments, 2015, pp. 1–4). The monitor is installed in parallel with the battery system to measure the current voltage of the batteries. Typically, a steady voltage of around 12.6 V is maintained in the battery, though this can vary depending on the size and design of the system (Thompson & Ford, 2023, p. 11). The GPIO pins of the INA219 are connected to the Raspberry Pi and, from there, inverters and other related equipment, such as relays, are controlled.

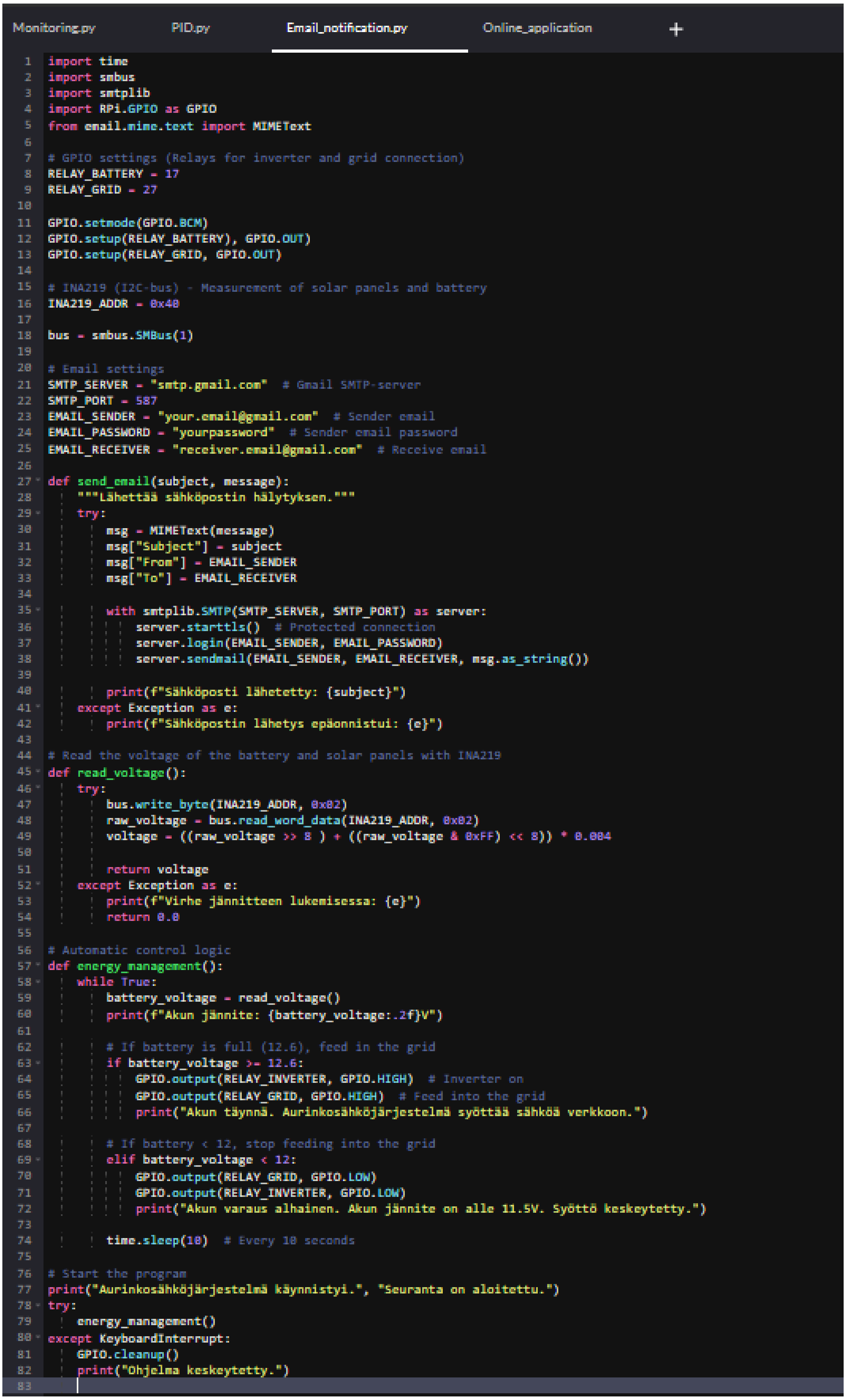
4.2.2 Program for the BMS

Using the code from Figure 8, the Raspberry Pi controls the battery load and inverter function. The INA219 module measures the current voltage of the battery system, determining whether to charge the batteries using relays. In addition, the user is notified via email as to whether the batteries are currently being charged. The code is written in Python to ensure consistency with the solar tracking system.

The time and Raspberry Pi GPIO libraries are installed for time-related tasks and to read and control the modules connected to GPIO pins. Figure 8 also shows that the program requires the smbus library to communicate with the INA219 module (ElectronicWings, n.d.). The smtlib and email.mime.text libraries are email-related and offer the possibility of sending an email via the SMTP protocol (Texeira et al., 2018, pp. 66–67).

The GPIO pins of the microcontroller are connected to relays that control whether power is directed to the grid or the batteries. One relay (RELAY_GRID) controls energy flow from the solar panels to the solar inverter and then to the electrical grid. The second relay (RELAY_BATTERY) directs energy to the batteries for charging. The GPIO.setup functions determine the relay pins as outputs, and the GPIO.output function sets the initial values to low, meaning the relays are off at the beginning of the program.

The INA219_ADDR determines the I2C address of the module, enabling the microcontroller to receive voltage data from the INA219 (Texas Instruments, 2015, p. 40). The Smbus.SMBus(1) function transfers data between the microcontroller and the module. With the INA219, raw voltage data can be read and used for programming purposes. Initially, however, the module provides the data in a different format, so it needs to be rearranged and scaled to use accurate voltage data from the batteries (Texas Instruments, 2015, pp. 12–15). If the measurement ever fails, a value of 0 is returned, which resets the program.



```python
import time
import smbus
import smtplib
import RPi.GPIO as GPIO
from email.mime.text import MIMEText

# GPIO settings (Relays for inverter and grid connection)
RELAY_BATTERY = 17
RELAY_GRID = 27

GPIO.setmode(GPIO.BCM)
GPIO.setup(RELAY_BATTERY), GPIO.OUT)
GPIO.setup(RELAY_GRID, GPIO.OUT)

# INA219 (I2C-bus) - Measurement of solar panels and battery
INA219_ADDR = 0x40

bus = smbus.SMBus(1)

# Email settings
SMTP_SERVER = "smtp.gmail.com"  # Gmail SMTP-server
SMTP_PORT = 587
EMAIL_SENDER = "your.email@gmail.com"  # Sender email
EMAIL_PASSWORD = "yourpassword"  # Sender email password
EMAIL_RECEIVER = "receiver.email@gmail.com"  # Receive email

def send_email(subject, message):
    """Lähettää sähköpostin hälytyksen."""
    try:
        msg = MIMEText(message)
        msg["Subject"] = subject
        msg["From"] = EMAIL_SENDER
        msg["To"] = EMAIL_RECEIVER

        with smtplib.SMTP(SMTP_SERVER, SMTP_PORT) as server:
            server.starttls()  # Protected connection
            server.login(EMAIL_SENDER, EMAIL_PASSWORD)
            server.sendmail(EMAIL_SENDER, EMAIL_RECEIVER, msg.as_string())

        print(f"Sähköposti lähetetty: {subject}")
    except Exception as e:
        print(f"Sähköpostin lähetys epäonnistui: {e}")

# Read the voltage of the battery and solar panels with INA219
def read_voltage():
    try:
        bus.write_byte(INA219_ADDR, 0x02)
        raw_voltage = bus.read_word_data(INA219_ADDR, 0x02)
        voltage = ((raw_voltage >> 8 ) + ((raw_voltage & 0xFF) << 8)) * 0.004

        return voltage
    except Exception as e:
        print(f"Virhe jännitteen lukemisessa: {e}")
        return 0.0

# Automatic control logic
def energy_management():
    while True:
        battery_voltage = read_voltage()
        print(f"Akun jännite: {battery_voltage:.2f}V")

        # If battery is full (12.6), feed in the grid
        if battery_voltage >= 12.6:
            GPIO.output(RELAY_INVERTER, GPIO.HIGH)  # Inverter on
            GPIO.output(RELAY_GRID, GPIO.HIGH)  # Feed into the grid
            print("Akun täynnä. Aurinkosähköjärjestelmä syöttää sähköä verkkoon.")

        # If battery < 12, stop feeding into the grid
        elif battery_voltage < 12:
            GPIO.output(RELAY_GRID, GPIO.LOW)
            GPIO.output(RELAY_INVERTER, GPIO.LOW)
            print("Akun varaus alhainen. Akun jännite on alle 11.5V. Syöttö keskeytetty.")

        time.sleep(10)  # Every 10 seconds

# Start the program
print("Aurinkosähköjärjestelmä käynnistyi.", "Seuranta on aloitettu.")
try:
    energy_management()
except KeyboardInterrupt:
    GPIO.cleanup()
    print("Ohjelma keskeytetty.")

```

Figure 8. Python code for BMS

The energy management system reads the voltage numbers from the batteries. Relay control is determined by a voltage measurement of between 12.0 and 12.6 V; if the voltage in the batteries exceeds 12.6 V, the solar panels will begin to send energy to the grid via the solar inverter. If the voltage is less than 12 V, the solar panels will divert the energy current into the batteries to charge them. This measurement between voltage numbers is taken every ten seconds.

The main loop informs the user via email when tracking has started. This is a continuous loop that monitors changes in energy management. The email is sent via SMTP settings. The settings chosen by the user determine the email services used, such as Gmail, and use a protected connection in the form of STARTTLS. (Adryan et al., 2017, pp. 329–330). When an email needs to be sent, it logs in to the email address of the sender and sends the email to the address of the recipient.

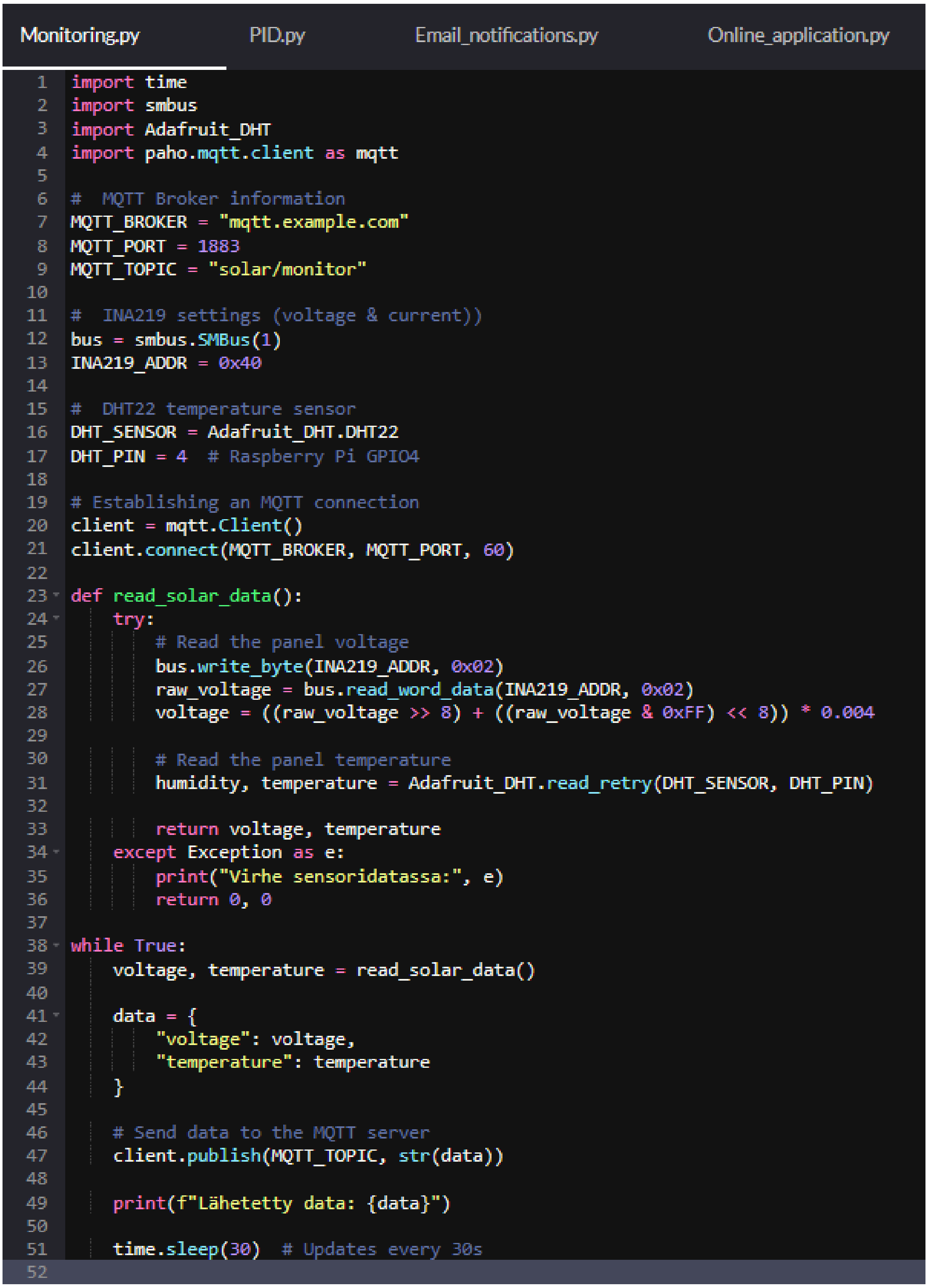
4.3 Remote monitoring of panel status

The same principle used in battery management systems allows users to monitor the status of a panel remotely. Still, users would find it irritating to receive a constant flow of emails about the panel status, so an external application could be used (Marshall & Rinaldi, 2017, pp. 208–210). Importing Paho MQTT Client into the Python code enables the creation of an application for monitoring the panel system using MQTT.

MQTT is a standard-based messaging protocol (Marshall & Rinaldi, 2017, pp. 208–210). It is a set of rules for machine-to-machine communication that is client-based. The system works by sending data from the panels to the data broker, which then delivers the data to users for monitoring. Python supports MQTT; however, as with sending emails, an internet connection is required.

Additional sensors can be added to the panel system. For example, this could be a temperature sensor to monitor the panel temperature. The Adafruit DHT22 temperature and humidity sensor could be used in the panels (Adafruit Industries, 2025, pp. 3–5). It is a cost-effective sensor with an integrated analogue-to-digital conversion system. Most

Adafruit devices have Python library functions related to them, which makes the sensor easy to integrate into the system when using a Raspberry Pi as a microcontroller.



```python
import time
import smbus
import Adafruit_DHT
import paho.mqtt.client as mqtt

#  MQTT Broker information
MQTT_BROKER = "mqtt.example.com"
MQTT_PORT = 1883
MQTT_TOPIC = "solar/monitor"

#  INA219 settings (voltage & current))
bus = smbus.SMBus(1)
INA219_ADDR = 0x40

#  DHT22 temperature sensor
DHT_SENSOR = Adafruit_DHT.DHT22
DHT_PIN = 4  # Raspberry Pi GPIO4

# Establishing an MQTT connection
client = mqtt.Client()
client.connect(MQTT_BROKER, MQTT_PORT, 60)

def read_solar_data():
    try:
        # Read the panel voltage
        bus.write_byte(INA219_ADDR, 0x02)
        raw_voltage = bus.read_word_data(INA219_ADDR, 0x02)
        voltage = ((raw_voltage >> 8) + ((raw_voltage & 0xFF) << 8)) * 0.004

        # Read the panel temperature
        humidity, temperature = Adafruit_DHT.read_retry(DHT_SENSOR, DHT_PIN)

        return voltage, temperature
    except Exception as e:
        print("Virhe sensoridatassa:", e)
        return 0, 0

while True:
    voltage, temperature = read_solar_data()

    data = {
        "voltage": voltage,
        "temperature": temperature
    }

    # Send data to the MQTT server
    client.publish(MQTT_TOPIC, str(data))

    print(f"Lähetetty data: {data}")

    time.sleep(30)  # Updates every 30s

```

Figure 9. Python code for value measurement.

The program shown in Figure 9 works by importing all the necessary libraries. As the INA219 model is used for voltage measurement, the smbus library is added once again. The other libraries include Adafruit_DHT for the sensor, time for time-related tasks and paho.mqtt.client for forming the connection to the MQTT data broker.

MQTT broker information is written. This includes the server address, and the port used for transferring information, the default value of which is usually 1883 (Adryan et al., 2017, p. 318). The topic ensures the organization and separation of data if it is implemented on a larger scale.

The addresses and GPIO pins are determined in the measurement units, and the connection to the MQTT broker is implemented. The INA219 module reads the raw voltage, which is scaled to the correct voltage. The DHT22 sensor reads the temperature based on the functions in the Adafruit library. These measurements are then returned and sent to the broker. This process updates every 30 seconds based on functions in the Adafruit library. These measurements are then returned and sent to the broker. This process updates every 30 seconds.

Since an internet connection is required to send information, it is important to have some form of data security (Gordon, 2022, p. 118). Data security involves protecting users against unauthorized access. This maintains privacy and ensures that data on the panels is not viewed by unauthorized individuals. Security also prevents the data from being corrupted deliberately by outside parties.

5 CONCLUSION

With traditional installation methods and careful planning, it is possible to enter the market with only basic components and knowledge of how to install them. Nevertheless, these technological solutions should be implemented in the future, as they produce solar energy more efficiently and make the maintenance of the panels easier. Customers can better understand how their panels work, as they are offered remote monitoring options.

However, all three of these solutions are speculative without a real physical prototype. They are still feasible to produce, albeit some modifications will probably be required for them to work properly. Research has shown that, with related equipment such as batteries, charge controllers and inverters, the efficiency of PV systems can be increased exponentially. Different types of panels can be considered for applications, especially new, emerging types such as perovskite solar panels. Additionally, customers can choose the inverter that best matches their needs.

The speculative use of microcontrollers in the research should be noted, as they are a flexible and necessary component for future solar markets. Most microcontrollers are connected to the internet via LAN or Wi-Fi, making them usable in online applications. Although remote monitoring was not completed due to limitations, with proper research, a real monitoring application for clients can be implemented. Example components for solar tracking and BMS can be adapted to better suit the needs of the client; the research shows that this can easily be implemented with flexible solutions.

Additional solutions can be implemented using a microcontroller. In the future, Grenia should focus on integrating this and other types of controllers into PV systems. The use of other electrical components, such as different types of sensors, converters and modules, should be researched to improve the efficiency of solar panel control systems. Also, the ability of microcontrollers to connect to the internet should be noted as the world gets more online, with valuable data that could be used for further research into how solar panels work more effectively.

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