Bilkent University

Spring 2021-2022

GE 301 Term Project

"*Graphene-Based Solar Cells in the context of Responsible Research and Innovation*"

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1. Introduction

As the world population rises, so does the demand for energy in order to maintain life on earth. However, supplying the ever-increasing energy demand of humankind is an intractable task considering the net-zero target of the UN to cut greenhouse gas emissions until 2050. This challenging goal requires a complete transformation regarding how humans produce, consume, transport, or basically how they think about energy. The energy sector is responsible for around three-quarters of the greenhouse gas emissions today, and replacing traditional non-renewable methods with renewable energy sources like solar or wind would reduce detrimental emissions to the atmosphere [1]. The share of renewables in global electricity generation was 23.2% in 2019, whereas solar energy accounted for only 3.1% of global electricity generation [2]. Thus, innovation of renewable sources of energy is key to having sustainable tools to generate energy and these endeavors are at the center of the transition to a less carbon-intensive and sustainable world.

Nanotechnology deals with the control of matter at the scale of 1-100 nanometers, and nanoelectronics is a branch of nanotech applied to electronic components. Nanoelectronics helps to stimulate the spread of renewable energy, especially by photovoltaics, by making them more affordable and efficient [3]. In our project, we partnered with researchers from Istanbul Technical University Nanotechnology Research Center. Their aim is to produce solar cells with graphene-based nanomaterials that are environment friendly, non-toxic, and have higher ranges of wavelengths to absorb sunlight. Although graphene-based nanomaterials have many promising applications in areas regarding energy generation, authors Luo et al. mentions that two issues need to be considered before its widespread commercial use: *(i)* the preparation of graphene-based nanomaterials with well-defined structures, and *(ii)* the controllable fabrication of these materials into functional devices. The researchers from ITU Nanotechnology Center work on three dimensions that also overlap with these common concerns, namely, *(i)* simulating the various combinations of graphene-based solar cells before its commercialization, *(ii)* synthesizing the solar cells, and *(iii)* fabrication of these cells into solar panels.

The goal of this paper is to provide further information on the mentioned innovation and evaluate possible issues that lie at the intersection of its social and technical reflections. "There are four dimensions to sustainable development – society, environment, culture and economy – which are intertwined, not separate." [8]. Based on our analysis, the research touches upon the societal, environmental, and economical aspects of the sustainable development. The researchers are developing an innovative product that aims to cost less while being more environment friendly, thus affecting the society in a positive way. The Responsible Research and Innovation theory will be used to analyze and evaluate the project. Anticipation and reflexivity dimensions of the RRI theory will be examined within the project's context.

2. Theory

While examining the innovation endeavours in our project, we observed that developing a technology is a process where multiple stakeholders from different backgrounds meet and each member of the community has different values with them. Though the innovation practices in our project are mostly concerned with technological applications and aspects of nanotechnology, the practical reflections of the related developments on society and the related societal stakeholders are prone to be overlooked. Thus, Responsible Research and Innovation (RRI) theory will be used to analyze the focal points of our project.

There exists four dimensions in RRI theory that researchers take cognizance of while they are in the process of developing new technologies. These are anticipation, inclusion, reflexivity and responsiveness. The anticipation dimension involves systematic evaluation of ideas aimed at enhancing resilience while revealing new opportunities for socially-sensitive risk research. Anticipation prompts researchers to ask what if questions, and lead them to think about unexpected risks at the beginning of new innovation journeys [4]. The second dimension is inclusion. The inclusion dimension refers to including external perspectives and opinions by organizing stakeholder engagement activities [5]. Methods for having external engagement to innovation processes include consensus conferences, citizens' juries, and deliberative mapping [6]. Reflexivity suggests innovations should reflect on socio-cultural contexts, norms, and the values they possess. The aim pursued by this dimension is to have better capacity in decision making processes [7]. Responsiveness dimension underlines the importance of the ability of innovators to react to changes in response to stakeholders, society's needs or changes in the practicalities of the related technologies. This dimension aims to keep the innovations aligned with societal values constantly and keeping the development options open for future generations [7]. Responsiveness becomes more vital when the future is not easily anticipated initially when innovators try to integrate societal issues into their research.

To embed these values into the research and to have responsible innovations, van de Poel suggests six lessons to consider while trying to effectuate RRI theory into reality. These are: *(i)* Strategize for stakeholder engagement, *(ii)* Broaden current assessments, *(iii)* Place values center stage, *(iv)* Experiment for responsiveness, *(v)* Monitor RRI progress, *(vi)* Aim for shared value. These six lessons aim to integrate the four dimensions into the innovation processes by highlighting the needs of society, values of all the stakeholders, and considering both the social and ethical aspects of the technology development process.

In our project, we observed that the researchers from ITU were aiming to replace silicon-based materials with graphene-based ones in solar cells which effectuates the broadening current assessments perspective of the RRI theory. The researchers also put environment as a value in the center stage of their research instead of durability or efficiency, which is an example of the third lesson of the RRI theory. Lastly, the research's goal is to have a sustainable innovative product that aims to serve shared values of the society, thus effectuating the last lesson of the theory, namely aiming for shared values. Incorporating RRI theory into the developments of nanotechnology can support research through improved communication with society while addressing the unexpected drawbacks of innovative products early in the innovation processes [1].

3. Background Research

3.1. History

The seeds of modern nanotechnology research began in 29 December 1959 when Richard P. Feynman started talking about possibilities on manipulating materials on smaller scales [9]. In fact since ancient times, people were unknowingly using nanotechnology to create various objects [9]. In the late 1990s and early 2000s, nanotechnology was seen as “the next industrial revolution” in the U.S. and the National Nanotechnology Initiative (NNI) was established [9][10]. Since the properties of materials changed on a small scale, nanotechnology was promising for technological developments, as materials could be made to have certain desired characteristics [9]. In the last twenty years, nanotechnology has developed significantly [10]. However, as this technology is new to our daily lives, it is still not certain what will happen when we are exposed to large quantities of nanoparticles [10]. Therefore, it is important to evaluate this technology from different perspectives, so that the technology development process is responsible [10].

3.2. Technical Aspects

3.2.1. Solar Cells & Solar Panels

Every day, the sun emits a massive quantity of energy in the form of heat and radiation, which is referred to as solar energy. Solar energy is an infinite source of energy that can be harvested at no cost. One significant advantage solar energy has over other traditional power generators is that sunlight may be directly converted to solar energy using small and tiny photovoltaic (PV) solar cells [11]. This big spherical gaseous cloud is mainly composed of several hydrogen nuclei combining to form helium energy with the emission of energy from the fusion of the hydrogen nuclei in the inner core of the Sun via nuclear fusion. During this process of fusion, four hydrogen atoms combine to form one helium atom with a loss of mass which is radiated as thermal energy [11]. This energy produced as a result of the fusion reactions is free from other by-products such as pollutants. For this reason, solar cells and the harvesting of solar energy can be considered as a clean energy technology.

Although solar cells can harvest solar energy and generate clean energy, the main problem is the efficiency of solar cells. There are a lot of different types of solar cells and they are typically named after the semiconducting material they are made of [12]. According to the data provided by the National Renewable Energy Laboratory, we can look at the highest confirmed conversion efficiencies for a range of different photovoltaic technologies. According to the data the efficiency can range between 13% to 47%. If we look at most used types of cells which are Crystalline Silicon Cells, they have a conversion rate changing between 21.2% and 27.6% [13]. Due to the efficiency and cost of producing solar cells there is a lot of research on alternative methods of creating solar cells both for cells aiming for lower costs and higher efficiencies [12].

3.2.2. Quantum Dot

Quantum dots can be described as human-made “droplets” of charge which can vary in the quantity of electrons they carry. A quantum dot can have a single electron or thousands. The size, shape and interactions of quantum dots can be precisely chosen using advanced nanofabrication technology. Although the size and shape of quantum dots can be changed their typical dimensions are in the range of nanometers to microns [14].

Quantum dots have been mainly used in applications such as biosensing and bioimaging. The quantum dots used in these processes have been mainly semiconductor quantum dots [15]. Despite their use in these fields, in the production of these quantum dots heavy metals are used. This problem leads to a limitation of semiconductor quantum dots due to toxicity [15][16]. In order to solve this problem, scientists have created carbon quantum dots (CQDs). CQDs are less toxic compared to semiconductor quantum dots and other than the benefit of lower toxicity, they are also more biocompatible and cost less [15][16].

Another type of quantum dot similar to CQDs are the Graphene Quantum Dots (GQDs). Similarly, GQDs are less toxic compared to semiconductor quantum dots and cost less to use. Apart from this property, GQDs have an exciting prospect in the use of photovoltaic devices due to their higher efficiency at absorbing incident light [16]. Due to their ability to absorb incident light and their less toxic nature, GQDs are a promising replacement for semiconductor quantum dots.

3.2.3. Nanotechnology

Nanotechnology is a type of technology which deals with different types of structure with dimensions of the order of a billionth of a metre. Nanotechnology is used in various fields such as the health sector, renewable energy or even the food industry [17]. In our project, we are focused on the applications of nanotechnology in the field of renewable energy, mainly photovoltaics. For solar cells, the most promising aspect of nanotechnology are the quantum dots which were discussed in the previous part. With advancements in the field of nanotechnology, the efficiency of solar cells can be increased as quantum dots can be used more effectively. The advancements in nanotechnology can also decrease the production and implementation cost of quantum dots [18].

3.3. Applications

The use of solar cell technology has been under the radar of attention due to the potential of being a partially cost efficient, lightweight and flexible way to produce photovoltaic (PV) energy [19][20]. Since PV solar cells has become considerably popular, many countries such as Gulf Cooperation Council (GCC) countries such as Qatar and Saudi Arabia where fuel oil to produce energy is common and China started promoting the PV solar cell industry in order to get in front of the issues that come within fuel oil usage such as carbon dioxide levels rising and thus ended up helping the solar cell producers to improve the solar cells to produce more energy [21][22][23][24]. Therefore in places where the sun time is longer than usual, such as California and most of the United States, PV usage is more common [25]. However, since the prices could be high while trying to produce a cleaner and stronger energy, this could result in some potential user loss if they are economically lacking such as the case seen with the Malaysian market [26][27]. In general, the industry is aiming to make the technologies affordable by groups like families and businesses for reasons such as reducing electricity bills and also increasing the building's overall value. One could also mention that PV technologies could be considered a relatively low risk-free investment for the financial community due to its safe and clean nature [28].

In order to provide the PV solar cell technology to a bigger population, the mass production of the product is a crucial step. Therefore during the mass production process, the factories and the engineers can be seen at the first levels. Factories are aiming to improve the current PV technology race by reducing the cost and improving the quality. For this reason, engineering teams are developing the project's industrialization by creating a unique software to simulate the purification process of the material being used to see the overall cost, manpower need, consumables and such [29]. These processes are all done because the PV technology providers are aiming to produce these cells for general energy production. Furthermore, in some other projects that are trying to aim for economic feasibility during the process, claim that the target audience for such study are decision makers including industry and government [30].

Looking at the overall achievements of PV energy production, it could be said that the technology itself is an important stepping stone for the future of sustainable energy for human civilization. Since high modularity and virtual usage anywhere is a specialty of solar PV technologies which separate it from other energy production methods, it can be used in different areas [28]. In the future with the development of solar energy technologies, solar PV energy could be used inside cars to provide energy instead of diesel and gas. Furthermore, it could be used in phones to charge them [28].

3.4. Safety and Risk

Although it is known today that solar energy is more efficient and cleaner in generating energy through conventional power plants, the production and operating methods of solar cells are neither completely safe nor ecological. It may pose potential health risks due to environmental conditions and associated toxic chemical products and materials used in its production. At the same time, in case of external factors, security situations that can cause electrical failures and fires can be seen.

Classification of Risks	Solutions
Laboratory ● Appropriate size and location with the project. ● Low Standard conditions (appropriate temperature, pressure, location of electrical cables, etc.) ● Difficulty in finding suitable skilled workers. ● Incorrect material use, incomplete labelling, not enough stock area, reactions of chemicals causing fire.	● The laboratory should be in the appropriate size and location with the project. ● Laboratories should provide standard conditions ● Qualification and knowledge of the researchers working in the laboratory minimizes situations such as incorrect material use, incomplete labelling, chemicals causing fire. ● Researchers working in the lab must wear appropriate clothing and accessories in line with the requirements of the project, otherwise it will lead to situations that threaten human health.

Technology ● Technology tie-up/Joint venture, expected lead time issues if any. ● Machinery breakdown and downtime	● Stay up-to-date and research and follow developments.
Malfunction ● As with many modern electronic devices, malfunctions can be observed in solar panels. ● This includes switches, fuses and wiring. Failure to do so results in damage, including electric shock and fire[35].	● Innovation, PV Stop, has recently been developed and is now used as a reactive solution to safely isolate the power produced by solar systems. ● Isolates the power produced by the system in seconds and eliminates the risk of high voltage DC electrocution. [31]
Fire & Ice ● A loose or poorly connected cable connection. ● A poor ground connection, or the use of spare parts that do not fit the particular unit can cause a fire [33]. ● At the same time, the high or low level of heat generated by the system may result from spontaneous combustion from parts inside the cell or in the surrounding environment. ● Depending on the fire, it can cause smoke and toxic by-products. [32][33].	● Using materials act like liquid tarp that can be sprayed over solar panels to block light from hitting the panels. [31] ● Using tolerant materials in the system. ● Minimizing electrical disturbances that could cause fire. ● Standardizing the temperature of the system taking into account the weather conditions
Toxicity ● Chemical materials such as arsenic and cadmium, in a process that produces a toxic by-product. ● Smoke and toxic byproducts to air occur result from fire or electrical failure [32]. ● Dangerous not only for the environment, but also for humans, domestic and wild animals.	● Modernization on electrical devices system ● Zero-emission – their functioning does not entail high emission of toxic substances into the atmosphere. [31] ● Silent –do not emit excessive noise, which is why they are entirely convenient, completely safe for humans and the natural environment. [31]
Grounding ● Electrical fault may occur, resulting in damage to the electrical system or even fire[33].	● Correct and regular grounding in accordance with the system. ● Regular check up.

Table 1: Risks and Solutions table

3.5. Sustainability

In the past years, it has become clear that humans should focus on searching for alternative energy sources, as fossil fuels and oil consumption could lead to an inhabitable world. Therefore, clean energy sources, such as solar energy, become a hot topic as clean technologies use sources that are easily available and renewable like the sunlight. Many institutions like NREL have been established to encourage clean energy research [36]. These technologies decrease the burden that humans put on Earth by saving on resources and preventing air pollution. While solar cells offer a sustainable solution to energy harvest, it is also important to be sustainable during solar panel production. In other words, the materials used for solar cells should not be harming the earth as well and should be easily accessible. While perovskite solar cells are widely used in order to increase the efficiency of solar harvesting, they contain elements that are considered hazardous [37]. It is important to find a balance between efficiency and using hazardous material to make sure solar cells are not diverging from their purpose of being clean energy sources [37]. Thus, it is important to research alternative materials for solar cells. In this case, nanotechnology comes into place as with nanotechnology it is possible to produce many eco-friendly solutions that are also efficient enough to be feasible [38]. Nanotechnology has been used for many years now to find solutions to energy conservation and to produce both feasible and eco-friendly renewable energy resources [38]. For example, with nanotechnology, it was possible to produce polymer solar cells, which are easier to dispose of than widely used silicon-based solar cells, as they are less toxic [38]. While nanotechnology offers promise to contribute to sustainability, it is also important to consider its risks, therefore it is important to use nanotechnology together with other disciplines like information science and environmental sectors, as Diallo et al point out [39].

4. Method

The field site of the project was found through a mutual acquaintance; therefore, the interviews were set up using WhatsApp. We examined a lab that was working on developing graphene based solar cells. Three interviews were made with three professors from the project who worked in different fields and were contributing to different parts of the project. Assoc. Prof. Şener Özönder is a physicist and he works on the machine learning part of the project. Prof. Dr. Levent Trabzon is a mechanical engineer and he works on the device assembly part of the project. Assist. Prof. Caner Unlu is a chemist and he works on the synthesis part of the project. The interviews were done through Zoom and were conducted in Turkish. Later on, these interviews were transcribed and translated to English. QDA Miner Lite was used to analyse the English transcripts of the interviews.

5. Findings

5.1. Technical Aspects

The technical aspects of the project were discussed in the interviews. These aspects are categorized below.

Technical Aspects	Interview Comments
Interdisciplinary	This project is about a technology that we are developing with people from four different science disciplines: chemistry department, physics department, electrical and electronics engineering department, and I am a mechanical engineer, mechanical engineering department. This is an interdisciplinary project, so for example, my colleagues would not be able to do what I can do. I cannot do what my colleagues can do. So, we formed a group where each of us complement the others in a way. [Levent Trabzon, Mechanical Engineer].
Machine Learning	We have a large parameter space. In this parameter space, if you consider that each graphene configuration takes eleven hours to calculate, as I just said, it is difficult to calculate all these one million possibilities using computers. That's where artificial intelligence and intelligent search algorithms come in. I cannot do grid search here, so I need to use more intelligent algorithms. It should find the graphene configuration that has the spectrum I want, or at least a configuration that is close to that spectrum. Here we use artificial intelligence. [Şener Özönder, Physicist]
Graphene Quantum Dots	They do not have a width, well like there are nanowires but these are not like planes or crystals, they are in nanoscale. That's why they are called quantum dots, and when you look at them under the light, especially when you use ultraviolet light, they emit light in different colours like this. In other words, you can make it give the wavelength of light you want by changing, especially the size of the quantum dot. [Şener Özönder, Physicist]
Device	I designed it, Prof. Caner synthesized it, but after it is synthesized, maybe it is something like a liquid in a small test tube. We have to turn it into a tool, into a device, into a sensor. We have to use other methods to do that. We have to mix it with something, we have to apply it on a surface, and then it has to dry. Then, again you need to add something, and then you have to solder the cables and so on. [Şener Özönder, Physicist]
Doping	When we dope graphene with some non-carbon elements such as boron, sulphur, phosphorus or nitrogen at such places, it affects the light absorbing properties of graphene. It may absorb at different wavelengths, or maybe it can absorb more. [Şener Özönder, Physicist]

Table 2: Technical Aspects and Comments table

5.2. Applications

Background research shows that the solar PV cells have many different stakeholders involved in the process such as local people, workers in factories, engineers, businesses, decision makers such as governments and therefore it also has many applications. Consequently, according to the interviews done, main stakeholders seem to be consisting of customers who are the general public and producers from other industries who may implement the technology being used in the project into other projects. Customers are mainly targeted from residential houses or businesses where there could be a need for electricity or hot water since solar cells could also help in that aspect. Furthermore, it was mentioned that the technology could be inserted into different areas such as the devices being sent into space. To add on to these current applications, the technology will be more widely used as it develops.

Hot Water	In residential houses, solar energy is mostly used for hot water... [Levent Trabzon, Mechanical Engineer]
Electricity	They are used for energy generation, recently they are building solar farms in our country... because of solar panels, people, companies... are using those farms to generate electricity [Levent Trabzon, Mechanical Engineer] Our intention is to produce this technology for the common public...We at least want cheap solar cells that can be used for each house to produce electricity [Caner Ünlü, Chemist]
Devices	It is in our cell phones, in our computers, many medical devices, it is actually everywhere when there is a chip involved. [Levent Trabzon, Mechanical Engineer]
Eco-friendly	Our main goal is to be pioneers, to produce, to develop eco-friendly solar cells that our people can use for streets, for their houses. [Caner Ünlü, Chemist] Perhaps, it may be possible to use it in plants as well in some cases... [Şener Özönder, Physicist]
Other	You can adapt these designs to install solar cells in elastic surfaces as well. [Levent Trabzon, Mechanical Engineer]

Table 3: Applications and Comments table

5.3. Safety and Risks

The project was shaped in the light of background research. Research shows us that heavy metal materials used in solar cells cause risk and safety problems in terms of toxicity. Therefore, carbon-based materials are used in the project and graphene comes to the fore. In the event of electrical failure and high heat that may arise as a result of a safety problem, measures have been taken in the name of emission and tried to minimize the problem so that the chemical toxic situation is not in question. Graphene and side materials used for the project to be environmentally friendly were determined. For situations such as grounding, fire, ice, the risk will be reduced if the human factor is also included in the project, and if the rules such as maintenance, repair of the system in case of malfunctions, and renewal and change related to the requirement are followed [33].

According to our interviews, when we talk about risk, we talk about technical risks regarding the production. Professors tell us at the beginning of the project, there are some risks when they are producing these quantum dots. However, they already covered the safety instructions for production during the project proposal. In the project they are going to use quantum dots, and they modify them with boron and nitrogen. This will change the light spectrum, so the solar panels will be able to absorb sunlight more. According to background research we know that quantum dots that they use are criticised, and people ask whether it can enter into the human body, through breathing.When we ask a question about this kind of safety issues, they reply that there is no such risk when you are using these solar cells, because the solar cells will be confined with a thin glass or a light-permeable polymer. So, there won't be any nanoparticles, quantum dots that are flying free in the air[34]. Consequently, people won't pose health issues when they are using solar cells by the project.

The risk and safety problems of the project were discussed in the interviews. These aspects are categorized below.

Chemical Risk	… avoid those heavy metals, heavy metal salts, or these chalcogenides, the materials we use are not as effective as them. [Caner Ünlü, Chemist]
Technological Risk	…risk that if it is a very large molecule, if it is over 200-300 atoms, it may not be possible to calculate it using computers. In other words, no matter how many supercomputers you use, the software has limitations and we may not be able to calculate molecules in huge sizes. [Şener Özönder, Physicist]
Economical Risk	…there is also a risk of being exposed to excessive heat and energy because of the machines that we use in production. We take precautions for these during the production of course, these are known techniques.[Levent Trabzon, Mechanical Engineer]
Lab Risk	… a toxic gas is released in the environment while we were working with toluene or sulfuric hydrogen sulphide, something like sulphur. We worked in systems that could take that gas, which we call fume cupboards, neutralise or remove it from the lab environment. In this way, we first protected ourselves. [Caner Ünlü, Chemist]

	…When we collected our waste, we did not throw it out to trash like that. There are certain waste collection places. There are chemical waste areas, we dumped it there. In this way, we have protected both ourselves and the environment as much as we can. [Caner Ünlü, Chemist]
Health Risk	…Sometimes quantum dots that we use are criticised, they ask whether it can enter into the human body, through breathing. There is no such risk when you are using these solar cells, because the solar cells will be confined with a thin glass or a light-permeable polymer. So, there won't be any nanoparticles, quantum dots that are flying free in the air. So, they won't pose health issues when you are using them.[Leven Trabzon, Mechanical Engineer]

Table 4: Risks and Comments table

5.4. Sustainability

The project was contributing to sustainability in many ways. The project considers all four important points of sustainable development which are society, environment, culture, and economy [40]. First of all, the aim of the research is to develop cheap and easily accessible solar cells, so that solar panel usage can be commonplace. This is an example of social sustainability as it shows that the researchers are considering society and their needs during the development process and that they are trying to create equal opportunity for everyone. This is the society aspect of sustainable development that was mentioned in Brundtland Report [40]. Moreover, the researchers use natural sources available in Turkey, like boron, when possible, which again shows that the researchers in this project are aware of the social and geographical context that they are in, and developing while considering these factors [41]. The use of natural resources available in the country and development of solar energy also shows that the researchers consider the economy part of the sustainable development as they provide an opportunity to be independent regarding energy. As Prof. Dr. Levent Trabzon says "If you use classical fossil fuels, you are bound to be dependent on someone else", so it is both economically and socially important to produce more accessible solar cells and use local sources.

Furthermore, an important result of solar energy becoming commonplace is that it will decrease the dependency on energy sources such as fossil fuels and oil, and the carbon emission to the atmosphere will decrease consequently, reducing our carbon footprint. Apart from developing a sustainable energy source, the project aims to use low toxicity elements for nature while developing these solar cells. These two points show that the project also fits to the environment side of sustainable development, as the research is shaped by environmental concerns as well. While lead, other heavy metals, and some rare elements are used to make solar cells, due to their high-efficiency rate, this project aims to use graphene, which is a carbon-based material. There is an efficiency versus ecology conflict here in the development of solar cells, and this project is a good example of responsible innovation as the researchers choose to focus on making eco-friendly materials more feasible for the future of solar cells rather than researching more about the toxic alternatives. The researchers aim to use materials that are abundant and safer for the environment in order to make the solar cells more accessible and decrease the toll on the earth at the same time.

When they use environmentally friendly materials, they ease the disposal process as well. When solar cells are used for industrial purposes, the companies could know how to dispose of components that contain heavy metals but this could have been a problem for private users, as they lack the connections and means to safely dispose of solar cells containing heavy metals.

Moreover, when they faced difficulties regarding the usage of less toxic materials such as durability issues of carbon, they tried to make their solution more feasible in order to promote the usage of less toxic solar cells. This is another value conflict, and the researchers again chose responsibility over durability in this case and instead of adding harmful materials to solar cells, they tried to make the environment-friendly materials economically desirable to compensate for the durability issue.

Sustainability - Renewable Energy Sources	But when you think from a sustainability perspective, when you think about the environmental perspective, there is a free-of-charge energy source. … according to some calculations, if you cover a land around Konya's size with solar panels, you will be able to sustain the whole world with energy … [Levent Trabzon, Mechanical Engineer] The sun, I mean the sunlight, is the most free-of-charge energy source for us. It is the most sustainable source that will be an energy source for millions and billions of years and will constantly warm us. While it is possible to use this resource easily and accessing this resource is actually not that difficult, the use of fossil-based sources, especially gasoline or such fuels, seems to have more impactful causes, or rather results, in nature. [Caner Ünlü, Chemist] … one of the most important things in the world right now is sustainability, using environmental and nature-friendly resources. Considering that the sun is the source of nature, it is one of our most important and fundamental tasks to use the sun as human beings. And it is also our task to use the sun in a way that is friendly to our environment. [Caner Ünlü, Chemist]
Social Sustainability - Accessibility	Instead of using heavy metals, we use what we get from the environment and produce solar cells. We produce materials with this kind of production mentality: more sustainable, more environmentally friendly, but also more accessible. Perhaps one of the biggest problems in the world right now is accessibility. … the Sun, even if you don't reach out to the sun, the sun will reach you. In other words, it is an energy source that constantly illuminates and warms the world. [Caner Ünlü, Chemist]
Efficiency vs Ecology	Our biggest problem was that, although we tried to avoid those heavy metals, heavy metal salts, or these chalcogenides, the materials we use are not as effective as them. … Our starting point was purely carbon-based materials but when carbon itself was not enough, we doped carbon with materials like nitrogen, sulphur, phosphor, boron, materials that can still be considered eco-friendly. [Caner Ünlü, Chemist]
Disposal of Carbon-Based Solar Cells	When you need to dispose of a broken solar cell, it can decompose in nature, so it is recyclable. [Caner Ünlü, Chemist]
Durability vs Ecology	… the second one was durability. 10 minutes after you make a solar cell, you cannot go like Ohh I broke the solar cell. .. But these factors can be tolerated when compared to benefits. For example, the price … even if it is 5 times less durable, renewed 5 times, you still spend less than half of the money required for solar cells with heavy metals, this is economically more profitable … All in all, even if there were some issues, we tried to come up with ways to compensate them. [Caner Ünlü, Chemist]

Table 5: Sustainability and Comments table

6. Analysis and Conclusions

From the findings section, it was observed that when the study was first being conducted by people from four different science disciplines, they were aiming to find a more affordable, sustainable and an efficient way to produce the solar cells using nanotechnology methods. The researchers first talked about how silicon-based material is more common in the solar cell industry however the energy produced from it could be increased [Levent Trabzon, Mechanical Engineer]. Therefore through research they decided to use graphene and its quantum dots in order to receive their values to somewhat strategize for stakeholder engagement. Even though who the first stakeholder they were aiming for was not mentioned directly during the interviews, it could be claimed to be the common public [Caner Ünlü, Chemist]. Through this choice of material they are choosing a less toxic way to produce their solar cells. Another way the researchers were providing anticipation was their simulations for the system. They claimed that through computer software simulations of purification of the material, they could somehow see possible risks and calculate how it would work out in real life [Şener Özönder, Physicist]. However, even if the program could calculate possible risks, during the real-life laboratory process there could always be unexpected risks and differences from the simulation. They even mentioned they were not expecting a perfect outcome at the first go, there was always some possibility for some unexpected risks.

Overall, the project is a good example of sustainable development as the researchers consider all four aspects of sustainable development and whenever there is a value conflict between using less toxic materials with technical problems such as efficiency or durability, they choose to be responsible and try to come up with solutions to avoid harmful materials to the environment.

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8. Appendices

8.1 Interviews

8.1.1 Interview with Şener Özönder

Şener Özönder: [00:00:11] Let me quickly make a presentation. The slides are from another presentation I made. There is another project I work on called TUBITAK 3500 which is about discovering the best materials by using artificial intelligence. Here's the project. The main goal is discovering any material with any characteristics that we want by using methods like artificial intelligence, intelligent search algorithms etc. since trying all the possibilities would be impossible. Of course, when we say material, any physical or chemical material can come into mind. Moreover, discovering medicines should come into mind. In other words, any chemical or physical material in any scale can be discovered using these methods. We do this project with professors from ITU, the one at the front is Professor Levent, the one at the left is Professor Caner and the one with the blue shirt is me. This project is about developing carbon based, environment friendly solar cells. ITU Project BAP office has given it. It was a project with a budget of 1 million. Of course, the main issue of the project here is to develop solar cells that are in solar panels. There are many steps to this project. For example, the graphene that will be used in solar panels should be synthesised. That part is mostly Professor Caner's part as he is a chemist. But the part where we simulate the characteristics of the synthesised material was my part. The part where the material was built into a physical gadget was Professor Levent's part. If we talk about my part, as you can see, what we call graphene here is a lot of carbon atoms. These blacks are carbon atoms, the surrounding whites are hydrogens, these other coloured ones could be nitrogen, or they can be any other dopant atom. When we dope graphene with some non-carbon elements such as boron, sulphur, phosphorus or nitrogen at such places, it affects the light absorbing properties of graphene. It may absorb at different wavelengths, or maybe it can absorb more. So how do we test this? I mean, it's not possible to synthesise all the possible types of graphene and measure them in the lab, one different each time. Therefore, we can simulate them in the computer environment. For example, if I had a graphene like the one that I show here, I could calculate how the light absorption spectrum of this configuration would be. In supercomputers, for example, this calculation took about eleven, twelve hours. Finally, we get the absorption graph like this, or namely, the absorption spectrum. And for example, this spectrum tells us, this graphene absorbs light at most around 300-350 nanometers. This roughly corresponds to ultraviolet light. Now, if it comes around

600 nanometers, this corresponds to mostly red light. The visible light range is roughly around 350 to 700-800 nanometers. Therefore, using computers, we can measure the properties of the graphene in different ways, like how the optical properties of graphene change by changing the size and shape of the graphene here, or by changing the dopant atoms in it and their amounts. So here comes the question, why is this important? In other words, why do we simulate something that a chemist can synthesise and measure in a day, using computers. Of course, this one molecule could take eleven hours to simulate, but I can use a lot of computers at the same time and calculate thousands of them in supercomputer clusters, actually in a day. Therefore, it speeds up the process. What happens next? Let's say, I tell my chemist friend the shape of a graphene molecule that has the certain optical properties that we want. I tell him, if we dope with phosphorus instead of nitrogen and add 5%, it gives the spectrum exactly as we want. I can tell, go on and synthesise this. And this speeds up the process. By the way, these are called graphene quantum dots. What I mean is that although these are big molecules, they are not like a wire or a surface, they are like dots. They do not have a width, well like there are nanowires but these are not like planes or crystals, they are in nanoscale. That's why they are called quantum dots, and when you look at them under the light, especially when you use ultraviolet light, they emit light in different colours like this. Where do people use these lights? For example, if you go to a store now, you can even see televisions with quantum dots there. In other words, you can make it give the wavelength of light you want by changing, especially the size of the quantum dot. That’s the core of the job. So, we calculate these things like optic and mechanical properties in supercomputer clusters. I only talked about optic properties, but there are many properties of the material and we can simulate them all in computers. What light will it absorb the most, or what light will it emit if it emits light? Or what are its other chemical properties? We can simulate these. Here, for example, you see the supercomputer cluster at ITU. I also did some of my calculations here. Well, there is a problem, there are millions of possibilities for graphene, right? How do we find the most suitable one? Let’s say I want it to absorb 400 nanometers more. How do I find this? The size and shape of this graphene, the type of dopant in it, the amount of that dopant; all of these actually change the wavelength at which the graphene will absorb light. There are millions of possibilities like different dopants in different places, at different percentages, and so on. Like we can use nitrogen, sulphur, or many other dopant atoms like boron. We have a large parameter space. In this parameter space, if you consider that each graphene configuration takes eleven hours to calculate, as I just said, it is difficult to calculate all these one million possibilities using computers. In other words, not only I cannot synthesise them in the laboratory, I cannot try all

the possibilities on the computers as well since these calculations take a long time. That's where artificial intelligence and intelligent search algorithms come in. I cannot do grid search here, so I need to use more intelligent algorithms. It should find the graphene configuration that has the spectrum I want, or at least a configuration that is close to that spectrum. Here we use artificial intelligence. For example, artificial intelligence goes, first calculates this, then examines how close it is to what I want. From there on, using a function called acquisition function, it builds a Gaussian model. And then it says, next I should calculate this configuration, because it may be closer to what I want. Then it calculates that configuration. There are two things called exploitation and exploration, do you know what they mean, have you heard these terms?

Dilruba Haliloğlu: [00:08:54] No, I haven't.

Şener Özönder: [00:08:55] Alright, exploitation means making use of and benefiting from resources. The other, exploration means to look for somewhere else. Here, in essence, you only have one function. Let's say this horizontal axis is the chemical space that you have. In other words, every dot in this horizontal axis is the shape of a different possible graphene molecule. And let's say the vertical axis values are values of one of the objective functions. For example, let's say there is a function like this and the graphene absorbs light at most 400 nanometers. So, what am I actually looking for? I'm looking for the maximum point of this function. Of course, I have to do a lot of trial and error to find the maximum point. For example, I try here, then I try there, I say ah, I go up, good, I come here. Then when I go a little further, I say, OK, I found one peak, but is this a global maxima or a local maxima? Of course, I don't know that. The algorithm here has to use exploitation since this point could be a local minima or maxima, but I want to find global extrema. This is a very typical logic used in many algorithms. These things I mentioned here are actually used in medicine discovery as well since what we call medicine is also a chemical. So, I just called this molecule in this example a graphene molecule, but this could be aspirin, or it could be something else. What happens when we swallow medicine? After these are digested in our body, they are in the blood circulatory system.

Şener Özönder: [00:10:46] Then they spread to all tissues using the blood circulatory system. Let's say that there are some proteins outside the cells in a certain tissue in your heart or brain. This thing like pasta you see over there is a protein. It is actually huge and there are certain regions on this protein. You want your medicine to dock in those areas. This is called docking. Of course, if the molecular structure of the medicine is not correct, it cannot fit here. I mean, it's like parking a car in a parking lot. It has to fit right there; you have to design your medicine that way. In other words, you cannot synthesise all the different possible medicines and give them to the patients and try them since this is very costly. By doing some simulations beforehand in computers, you can actually speed up that process. To sum up, by using computers, simulations and artificial intelligence, we can discover new materials. But our main topic here is graphene extracts and the reason why we use them is because they are eco-friendly. In some quantum dots, toxic elements such as cadmium or indium could be used. These elements are toxic for nature and living creatures. But since graphene, and also us, human beings, are made of carbon, graphene is actually not toxic in that sense, it is eco-friendly. It can also be synthesised quickly; it is easy to manufacture, and maybe cheaper. It also has these types of features. In short, I hope you got the general idea. We can move on to your questions.

Dilruba Haliloğlu: [00:12:43] Thank you very much. The first question was related to what you do in the project and you already explained it in your presentation. I also read the interview you sent, so I knew you were using machine learning and things like that to produce materials.

Şener Özönder: [00:13:02] Yes.

Dilruba Haliloğlu: [00:13:04] Let me ask first, I read something about graphene. There is apparently research that suggests it can be toxic in large amounts. What about this issue, does this risk exist? For example, did you do anything to prevent this toxicity?

Şener Özönder: [00:13:22] Of course, graphene may be toxic if it enters the human body and accumulates too much in a tissue there. If you swallow it, it will probably be digested since it's carbon-based. But let's say it somehow got into a tissue, let’s say it's injected or something. If the amount is large, that tissue will probably try to wrap and contain it. But of course, we talk about solar cells here, and people do not take solar cells into their bodies. If we compare it with other toxic elements, like indium and cadmium that I have just mentioned, which are very toxic materials that should not be exposed to nature, graphene is not like them. When we say graphene exposure, for example if you take a pencil in your hand, when you draw with that pencil, it actually leaves graphene layers on that paper, that is what actually graphene is. What we call graphite is what is inside of a pencil. Graphite is made up of many layers of graphene stacked together and graphene is one of those layers. If it was a very toxic thing, people wouldn't use it daily, they wouldn't let children use it.

Dilruba Haliloğlu: [00:14:45] I am also writing with a pencil now. As you said, if it were problematic, I would have also been poisoned now.

Şener Özönder: [00:14:50] Yes, of course.

Dilruba Haliloğlu: [00:14:55] Who will be the main users of your product? Where do you plan to implement it later on?

Şener Özönder: [00:15:01] The main use of this material is solar cells. Since it can absorb ultraviolet lights very well, it will actually increase the performance of solar cells. Normally light reaches us at all wavelengths. In other words, while there are visible wavelengths, there are also invisible wavelengths, like ultraviolet and infrared light. Therefore, absorbing these invisible wavelengths as well and generating electricity from them is something that increases the performance of the solar cells. So, this material will be used in solar cells. Perhaps, it may be possible to use it in plants as well in some cases. This is a slightly different project; this is not a part of the project. But, you know, plants photosynthesise. The chlorophyll in plants uses certain wavelengths during photosynthesis, especially visible wavelengths. But let's think about this case; you want to grow plants in space. Maybe there is much more ultraviolet light in space than the visible wavelength. You might also want to use that ultraviolet light. For example, let’s say this graphene absorbs ultraviolet light very well, and emits light in visible wavelength. Therefore, it can absorb ultraviolet light and provide the plant with the visible wavelength it needs; thus, it actually helps photosynthesis. So, it is possible that graphene can be used not only in solar cells, but also in different cases. Similarly, for example, there is a company, established by some professors from Koc, I guess. Imagine that you made a label with this material, but it does not emit light normally, you cannot see what is written on that label. But when you look at it under ultraviolet light, it emits, just like I have shown here, visible light. So, if the ink is graphene-based, the label starts to become visible when ultraviolet light is reflected on it. There can be many different applications like these, but our focus here is actually solar cells.

Dilruba Haliloğlu: [00:17:58] And what if I ask how do you use solar panels later on?

Şener Özönder: [00:18:04] We make solar cells. First of all, there is the chemistry part of the project. We need to combine some other materials and make a device, like small things, microchips are needed. What are their features? When the light reaches it, it does the opposite of the diode lights. So, diode lights turn on when we give electricity. It actually works the opposite. Therefore, when light reaches it, it creates an electric current. You have to bring these solar cells, which are subject to this electric current, together. Then you bring those structures together again as a solar panel. You run electrical wires between them. In fact, the solar panel is the macro version of solar cells. Imagine a camera, or a cell phone camera, which is made up of these little pixels. Here, each pixel is actually a sensor, like a solar cell, sensitive to light. You put those pixels together and make a camera. Similarly, you can put these devices together and make a solar panel. Of course, where can you use the solar panel? In the industry for example. In order to produce large amounts of electricity, you can install solar panels on a very large land. But you can also install them on your roof. Or you could make a solar-powered calculator without batteries. You can actually use them in many places.

Dilruba Haliloğlu: [00:19:46] You have already mentioned that the project is interdisciplinary. Prof. Caner works in the chemistry department, Prof. Levent works in the mechanical engineering department. Are there any other people working on this subject? Or is it limited to these areas, computer science, chemistry and mechanical engineering?

Şener Özönder: [00:20:03] That's all for this part of the project actually. Prof. Caner synthesises in the laboratory in person, he is a chemist. I am a physicist. I'm mostly using computers. I do calculations relating to computational chemistry or let's say computational material sciences. So, I'm on the computational chemistry side. I do computational chemistry calculations using computers. Prof. Levent is a lecturer in the department of mechanical engineering, but actually he is also a physicist. So, he is working on subjects relating to physics, nanotechnology and materials science. He also works in the laboratory environment. He is on the device part of the project. I mean, okay, we produced this material, I designed it, Prof. Caner synthesised it, but after it is synthesised, maybe it is something like a liquid in a small test tube. We have to turn it into a tool, into a device, into a sensor. We have to use other methods to do that. We have to mix it with something, we have to apply it on a surface, and then it has to dry. Then, again you need to add something, and then you have to solder the cables and so on. That is a completely different process, so Prof. Levent works on that part of the project.

Dilruba Haliloğlu: [00:21:30] Thank you very much. Also, I was going to ask you, what kind of risks did you encounter in this regard, whether in the laboratory environment or when you used solar cells themselves? What did you do to fix the technology, or to deal with these risks when you faced them?

Şener Özönder: [00:21:53] Yes, there are always risks. In fact, we must write them down while proposing the project. What types of risks are there? First, there may be risks related to the project, in other words relating to the topic of the project. For example, what do we want here? Let me tell you the part that I work on; we want to calculate the optical properties of a graphene material. But, for example, there is a risk that if it is a very large molecule, if it is over 200-300 atoms, it may not be possible to calculate it using computers. In other words, no matter how many supercomputers you use, the software has limitations and we may not be able to calculate molecules in huge sizes. For example, I think this molecule here is 1.5 nanometers to 1.5 nanometers. You can make smaller graphenes, like 1 nanometer to 1 nanometer. The largest molecule that I calculated was 2 nanometers to 2 nanometers. But, for example, we cannot calculate a graphene that is 3 nanometers to 3 nanometers. I mean, the memory requirement of the computer for this task, or let me say the complexity of the task is n to the three or four. For example, if we have ten atoms, let's assume the complexity is n to the three, we would not mind if it takes a thousand minutes. But when you go from ten atoms to hundreds, it gets more and more difficult because the time complexity is cubic. In other words, if the complexity was linear, we may have been able to handle it, but we cannot increase our computer resources cubically. So, we have limitations. Apart from that, the software we use may have some risks. This is more technical, but for example we use atoms of different elements and the software can't calculate the properties exactly as we want. The calculations somehow do not converge, it gets stuck somehow, and it is taking too long. Other than these, what could happen? For example, there may be problems on the synthesis side. There may be challenges on the chemistry side, for example I can calculate the molecule like this. Let's say I dope with nitrogen, or I don't know, I dope with sulphur or maybe I can use magnesium as dopant, for example. While I'm calculating here, I can do this, but for a chemist, it may be very difficult to synthesise a molecule with magnesium dopant in the laboratory. Therefore, everything I do on a computer, a chemist may not be able to do in a laboratory. In other words, not all elements are the same for him. For example, maybe magnesium ignites very easily. Or there may be another element that cannot be used for different reasons in the synthesis process. So, each of those elements actually has different characteristics. It's all the same for me, so I can take out what I want, put what I want and calculate it, but it's not like that in the laboratory. Apart from that, there are also difficulties on the device side, that is Prof. Levent's expertise. For example, Prof. Caner may have synthesised what you have calculated and put it in the test tubes. It can absorb the wavelength we want and emit the visible wavelength we want just like the example on this screen. But using this out of the lab, making that liquid graphene into a sensor would pose different challenges and difficulties.

Şener Özönder: [00:25:57] So how are you going to attach it to a wall or a surface? Maybe the features we want will go away when you put it on a surface. There are many such challenges on that side as well. Therefore, there are always such technical difficulties and risks. But of course, you try to anticipate them from the beginning and you make backup plans. If this happens, I try that, if that happens, I try this etc. Apart from these, there may also be risks related to the infrastructure. For example, I'm using the supercomputers at ITU. What do I do when there is a long waiting line there? For example, there is another national supercomputer system in Ankara called TRUBA. I'll try to use that system then; this could be my plan B. Or maybe there can be a flood, it has happened a few times before, in that section with supercomputers. Or it can get very hot because of the air conditioners. These are special system rooms and sometimes, the air conditioners do not work, so they have to shut down the system. These things happened before. The calculations are interrupted in the middle and you have to start all over again. So this kind of infrastructure risks are there as well. Or, maybe, you cannot acquire the materials that you need, they may be stuck in customs. So, it is necessary to foresee such risks in advance. But after all, this is a scientific research and development project, it is normal to have some risks. In fact, what we calculated in the simulation process, what we synthesised may be not suitable for making devices, maybe it is not possible to do such a device. But of course, there is no risk-free R&D project. So, risk is part of R&D projects. In fact, if there were no risks, if it was something done, something known, this would not be a research topic.

Dilruba Haliloğlu: [00:27:53] You are right. It is interesting that there was a flood. Did it happen when it snowed?

Şener Özönder: [00:27:58] No, it did not happen when it snowed, it happened some other time. After all, the system room is in a building. All kinds of fires, floods and such things can happen in that building, and they do. Therefore, such risks can affect your work. In the end, we have to turn off those computers.

Dilruba Haliloğlu: [00:28:21] Yes, it is true. You have already mentioned a little bit about it, but let me finally ask this again. You said, for example, we can also use graphene for plants in the future if we go into space. Where else can we use this technology in the future? Let me phrase it this way, what is the future of this technology?

Şener Özönder: [00:28:44] Graphene quantum dots are actually used in many places. In other words, if we search for applications of graphene quantum dots, we can see that it is used in so many places. Actually, google using this keyword and look at google images. You will see beautiful images. For example, it can be used not only in solar cells, but also in fuel cells, and in electric vehicle batteries. Here we are interested in optical properties of graphene but it has other properties that people can use. Today, we are trying to make smaller and smaller microchips or transistors. Graphene can be used for this, for example, when you need very high-frequency microchips in some cases, you can use graphene. It is also used as a sensor. So, these things are possible too. You can do many things by doping graphene with some other molecules, molecule groups with functional molecules. Even something like this was done in the laboratory environment, there is a protein called ACE2 that covid virus uses as a receptor. This protein is a chemical molecule as well, so you stick ACE2 on graphene. When covid virus binds to ACE2, it changes the electrical properties of graphene, the current through the graphene changes. You can also use it as a covid sensor. Of course, it has not been commercialised yet, it only exists in the laboratory. As I said, the commercialization of something is a very different field. Many good ideas exist in laboratory environments but somehow, they are not able to be commercialised. For example, you produce a microchip in a laboratory environment, and there are many expensive devices in the room, powering one microchip. Ok, you made a very nice microchip, but this does not always work, you need to be able to mass produce it. For example, if you produced that microchip in three months, the idea is very nice, but it is not commercialised. You can produce that microchip in three months, but, maybe, in Taiwan, in China, they can produce millions of microchips a day in the factories. So, mass production is very important. Where else is graphene used? It has uses in the health industry. For example, in order to detect anomalies in the immune system, you dope graphene with some chemicals and proteins, and the graphene itself does not interact with human body but there are proteins and chemicals that interact with the body, and when they bind to someplace in human body, it affects the properties of graphene. For example, the optical properties can be affected. In this case, by looking at optical emissions of graphene, you can produce diagnostic kits, especially relating to the immune system. These have all been researched and made before. There are plenty of articles and images on the internet. It is not possible to list them all, graphene is used really in many areas. You can see more details about them on the internet.

8.1.2 Interview with Levent Trabzon

Dilruba Haliloğlu: [00:00:02] Ok, we can start with our first question. First, could you tell us about your project?

Levent Trabzon: [00:00:16] The main purpose of the project is developing solar cells. It is a subject that has been studied for perhaps 60-70 years. The physics of the solar cells has actually been known for maybe 100 years, but the main problem is with efficiency. The sun is a very powerful energy source, solar energy. But in order to convert this source into usable energy, you know, efficiency is generally the difference between input and output, how much input is given and how much output is received. Generally, a silicon-based technology is dominant in the industry, and it has variations as well, you can use it in different ways. For example, there is amorphous silicon, there is poly silicon, and there is single crystal silicon. Normally, the solar panels on our homes are made of the type of silicon that is the cheapest and the easiest to produce. They are usually amorphous and polysilicon and their efficiency yields vary between three and ten percent. So, there are many technological options in solar panel production. But, think about it, you get 100 units of energy from the sun and you get roughly ten units or three units. Relatively speaking this is not efficient or profitable. But since the resource is free, the energy comes for free. But of course, it would be better if we can increase it. With some special techniques, the efficiency can go up to 50%, like using special dopants. But these are costly, so you cannot use it frequently, you cannot use it in every situation. Where could you use it? In cost effective situations. For example, in the Hubble telescope or the latest James Webb telescope, in cases where we need to be able to harvest energy very well, we can disregard the cost and use the best technology available. This project is about a technology that we are developing with people from four different science disciplines: chemistry department, physics department, electrical and electronics engineering department, and I am a mechanical engineer, mechanical engineering department. This is an interdisciplinary project, so for example, my colleagues would not be able to do what I can do. I cannot do what my colleagues can do. So, we formed a group where each of us complement the others in a way. And maybe you should take a look at this data. There is an interesting thing about solar energy called NREL. There is a graph called Best Research Cell Efficiency, which is renewed every year. It is a source form the US government, if you search as NREL. They mentioned the latest situation is solar energy research like solar efficiency, what changes have been made, how much progress has been made, and things like who did the research, A company, B university and so on. At the right bottom corner, you can see quantum dots. The energy efficiency values of quantum dots are less than some fantastic technologies. But it is a technology that started to show up after 2010, and this graph is made from stacking the data since 1975. So, we have decided to develop solar energy using these quantum dots that came about in the last 10 years. And our main goal was to increase the efficiency rates higher than what was built, you can see that it is 17-18% percent in this graph. That was our goal. By using engineering and other types of approaches, we wanted to develop quantum dots that can absorb a wide range of wavelengths of light and that are cheap and easy to produce at the same time. We wanted to integrate this into polymers, I mean this is standard and basic, our goal, what I want to emphasise is, we wanted to produce cheap, practical and easy to produce solar cells. Otherwise, as I said, there are many exotic and exciting solutions out there. But what we wanted to do here is something that many people do not look into, and we wanted to be pioneers of this in our country. This can sum up our project.

Dilruba Haliloğlu: [00:05:48] What will be the main applications of this technology after it is developed?

Levent Trabzon: [00:05:59] Now you may be observing where the solar cells are used in our daily lives. As I have said before, they are used for energy generation, recently they are building solar farms in our country, like there is a big project now in Konya. And for example, when you go on holiday, generally around Eastern Anatolia where it is usually sunny, you see dark coloured farms, like they are painted in black. That is actually because of solar panels, people, companies, settlements are using those farms to generate electricity. Generating electrical energy is the main use of this technology, in other words generating solar energy. In residential houses, solar energy is mostly used for hot water, as you know the panels absorb heat so you get heat by running water through thin pipes around solar cells. These are the most common ones. Our main goal was to produce electricity. Guys, the important part is efficiency. Could this be cheaper? Can I produce it with less cost? And the third is can I produce it easily? So, we should have cheap and at the same time easy to produce solar cells. You can also add one more, reliability. If you want to mass produce, produce for large scale projects, you need reliability. How long will these last, what will be their lifetime? Will it break quickly or will defects relating to electronics or materials affect its function? So, we can use solar cells for all of this, guys, for electric generation. It is common all around the world. They even used them in devices sent to space for these reasons.

Dilruba Haliloğlu: [00:08:03] You said it can be used in residential houses. So, all of us will be the users of this technology as well, right?

Levent Trabzon: [00:08:07] It can be used in residential houses. Actually, we have not thought about this in the scope of this project but you can adapt these designs to install solar cells in elastic surfaces as well. Then there are some different technologies, practices used. For example, you can wrap them like blankets and like you are going on trekking, you will put this in the bag and unwrap it when you need energy, things like that. So, what I am saying is that you can use solar cells when there is a need for energy, when you cannot generate it in large amounts, be it in the middle of the city or someplace far away. For example, you are travelling in the sea, like in a cargo ship or your private yacht. Or maybe not a yacht, something bigger. You need energy, and where would you get that energy? We call this harvesting, energy harvesting. Sometimes you can get this energy from the wind or water waves or oscillations and mostly from the sun which always shines on us.

İlknur Yılmaz: [00:09:26] May I ask a question? You mentioned reliability. Could you tell us more about the risks relating to this project? Like what kind of risks people may encounter?

Levent Trabzon: [00:09:45] So, when we talk about risk we can talk about some technical risks regarding the production. But maybe you are talking about this: we are going to use quantum dots, and we will modify them with boron and nitrogen. This will change the light spectrum, so the solar panels will be able to absorb sunlight more. Sometimes quantum dots that we use are criticised, they ask whether it can enter into the human body, through breathing. There is no such risk when you are using these solar cells, because the solar cells will be confined with a thin glass or a light-permeable polymer. So, there won't be any nanoparticles, quantum dots that are flying free in the air. So, they won't pose health issues when you are using them. Now, there are some risks when you are producing these quantum dots. But we already covered the safety instructions for production during the project proposal, these are more detailed parts of the project. Let's say you produced them.

Dilruba Haliloğlu: [00:11:19] What are the risks when you are producing this material, could you also talk about that?

Levent Trabzon: [00:11:24] Are you talking about technical risks?

Dilruba Haliloğlu: [00:11:26] For example, do quantum dots affect people who are producing them?

Levent Trabzon: [00:11:31] So, you may not be able to produce quantum dots as pure as you want, or you may not be able to collect them at the rate you want to and even when you do, its absorption window could be not what you want, it may be too wide, you may want to make it more precise. Or it may not correspond to your targeted wavelengths, for example, when you produce solar cells, when you are integrating quantum dots to polymers, the mixture may not be homogenous. And this may cause problems when you make electrode-electrolyte interfaces, in other words connection points of the device. Well, you are going to store the energy from electrons in the solar cells and you may not be able to carry enough electrons there. The defects on the interface and the polymer material can get the electrons of those atoms. We call this a defect, and this problem decreases efficiency. Our goal is over 20%, so we promised 20% but we aim even higher. First you do science and you do a proof-of-concept design, then you do fine tuning, this fine tuning is between science and engineering in a way. So, when you understand the science, you can do the fine tuning from an engineering perspective. I can roughly say these.

Dilruba Haliloğlu: [00:13:11] Are there any health risks when you are producing quantum dots? I actually wanted to ask that.

Levent Trabzon: [00:13:16] So, you need to take precautions of course. Because you know quantum dots are in nanoscale, so we can assume that there is almost no gravitational force on them. Since the mass in m.g formula is very small, it has no effect, so gravity has almost no effect. So, these particles can float in the air. Moreover, we need to take required precautions and check things like masks. Of course, there is also a risk of being exposed to excessive heat and energy because of the machines that we use in production. We take precautions for these during the production of course, these are known techniques. If you do not take these precautions, of course the nanoparticles can be harmful. But I also want to emphasise here that, in our laboratories what we are going to do are some prototypes. So, we are not going to make 10, 20,30 hundred thousand of these. That is the mass production part, and as an academician, a scientist, that is not my area, I cannot do that part that is another expertise. I mean I can do it, but I need to diverge my energy there, so like I need to clone myself if I want to focus on both sides, they are different fields. Moreover, you may need some practical experience in mass production that I do not have, so I may not be able to do everything as well. So, when the scale is bigger, that is another story, guys. The precautions there, the procedure there would be different. We are taking our own precautions during R&D projects. My students, who are a couple years older than you are, are doing the production and we teach them all these precautions.

Dilruba Haliloğlu: [00:15:07] Did you choose graphene for this purpose? Because I guess it is more dangerous to use silicon inside solar cells? Or am I mistaken?

Levent Trabzon: [00:15:16] No silicon is not harmful. As you know there are different kinds of graphene and we are going to produce graphene-based quantum dots by changing the atomic arrangements … You were studying computer engineering right Dilruba? What about you Ece? What was your major?

Ece Teker: [00:15:47] I am studying computer engineering.

Levent Trabzon: [00:15:49] What about you Ilknur?

İlknur Yılmaz: [00:15:51] I am studying industrial engineering.

Levent Trabzon: [00:15:52] Then artificial intelligence is your area of study, all three of yours, modelling and algorithms, the things I am talking about right now. Have you taken a course on material science yet? You haven't? Then let me roughly explain like this. There are gaps like this. So, imagine something small, like an ant. How will an ant here go there? When there is no connection, this is not possible. You need to make a bridge here, right? If you make that bridge, then that ant can go up there smoothly. Electrons work in a similar way. When you change the atomic arrangements of materials with quantum dots, you are changing this gap, you enlarge it or make it smaller. Now there are different wavelengths of sunlight right, there is visible wavelength, around 400-600, and there is UV and infrared, which has less energy. Our goal here is to change this gap in order to move the electron from here to there using energy coming from the sun. So, roughly speaking, by producing quantum dots, we can modify this gap just like we want, that is the main part, that was our goal guys. And because of that, maybe you have seen images of graphene as thin sheets, there are those kinds of graphene, we won't use those, we will use very small ones that have smaller surface areas.

Dilruba Haliloğlu: [00:17:38] What are your sustainability goals in this research? This project is important for sustainability, obviously, you develop a technology for solar energy.

Levent Trabzon: [00:17:51] You all know about this last energy crisis we are going through. If you use classical fossil fuels, you are bound to be dependent on someone else. And be it petrol, be it petrol-based products, these are not free of charge. You have to bring them here using pipelines etc. Even if it is in our own country, you need to dig down for thousands of kilometres. These are all difficult things to do. But when you think from a sustainability perspective, when you think about the environmental perspective, there is a free-of-charge energy source. And let me tell you this, according to some calculations, if you cover a land around Konya's size with solar panels, you will be able to sustain the whole world with energy, roughly speaking of course. Actually, there should be a famous diagram, it was here, I guess… Well anyway, you can check that out. Solar energy is way more sustainable than nuclear energy which has many sustainability risks, or petroleum which has political and economic risks. Solar energy is very sustainable and popular now, both for R&D and for production. For example, right now, if you want to make silicon-based solar cells and you say, I want to buy silicon wafers, you have to get in line. It is too hard to find one since the demand is really high.

Dilruba Haliloğlu: [00:19:38] And we wanted to ask … Or maybe one of my friends would like to ask a question. I talked a lot.

Levent Trabzon: [00:19:50] Ece you did not ask yet I suppose.

Ece Teker: [00:19:51] What are your thoughts on the future of nanotechnology and the future of solar energy with nanotechnology?

Levent Trabzon: [00:20:06] Nanotechnology research as you know starts with the foundation of STM in 1982 in modern age. But this does not mean it was not used before, in 1400-1573's Mimar Sinan used nanotechnology in Beyazit II Mosque, I tell this in my classes. This is a discovery that we have found. Later on, for centuries, it was used in Sam swords and in the renaissance, it was used for glass and gold and silver. But why is it important to us this much in this age? Because now we can see the atoms, we can manipulate them. When you consider the development of technology, how many years has it been? 30-35 years, not so much. But we are using nanotechnology in 7, 8 thousand products already in daily life. It is in our cell phones, in our computers, many medical devices, it is actually everywhere when there is a chip involved. And this is not all there is. You can find it in glass optics, clothes, walls, cars, and in many other places. Over 5 thousand or around 10 thousand, and there are many applications about it. I mean, you are very lucky, because you are probably 22-23 years old. You are the generation that will see nanotechnology used frequently in daily life, you'll see its applications. It has been 4-5 years since nanotechnology has been effective in our lives and we perceive that it will continue to stay common until the 2100s. Around those years, something new can come up, actually we predict that something new will come up, you can see that in the graphs. In Turkey too, we are coming to the age of nanotechnology, there are many internationally known Turkish nanotechnology companies, there are companies that young people like you started. So, there are various activities relating to nanotechnology. When we think about solar cells and nanotech, not only quantum dots, if you look at the chart, you'll see, there are many methods, and I am sure that we will develop more efficient cells in the future, as long as this progress continues, and I don't something like a nuclear war or political war does not start. I am expecting to see this development.

Dilruba Haliloğlu: [00:23:10] Thank you again for sparing the time to answer our questions.

8.1.3 Interview with Caner Ünlü

Dilruba Haliloğlu: [00:01:04] To start with, could you tell us about your project?

Caner Ünlü: [00:01:09] The main purpose of our project is this: as you know, solar cells are usually made from materials that contain heavy metals which are toxic and could harm the environment and cause unintended effects after they are no longer used. Moreover, they usually try to produce high performance solar cells using heavy metals or scarce elements. We are trying to get rid of this dependency on heavy metals and scarce elements, so we are looking for eco-friendly alternatives. We are looking for especially carbon-based alternatives, along with carbon we are using nano materials that contain nitrogen, sulphur and boron, although the last two are not as harmless as carbon and nitrogen. We are trying to produce eco-friendly, cheap and less harmless alternatives to heavy metals and heavy metal salts used in solar cells.

Dilruba Haliloğlu: [00:02:40] You've mentioned that usually heavy metals are used for producing solar cells. Are there any risks to what you are using now? So, what I am trying to ask is that, does graphene have risks? Or are there risks of solar panels regardless of the material used? Are there any risks for users or producers like you?

Caner Ünlü: [00:03:03] Actually, this is one of the main issues that we are aiming to solve, we are trying to use the least risky materials possible to produce solar cells. The things normally used in solar cells are lead, sulphide or cadmium telluride, things that are toxic, poisonous, and not that easy to produce, and that are troublesome to dispose of. If we return to your question, are solar cells that we produce harmful? While we are producing these materials, we use natural biomolecules, or actually they can be synthetic too, but at least we use materials that are biology-based like citric acid. Where is citric acid found? For example, in lemon salt (TN: Turkish for citric acid, used in daily context), this is our source for carbon. Where is urea found? It is found in the urine. It's our source for nitrogen. By using such materials, we are trying to produce solar cells with minimum toxicity, as minimum cost as possible, and with maximum income.

Dilruba Haliloğlu: [00:04:12] Who will be the main users of this technology?

Caner Ünlü: [00:04:16] Our intention is to produce this technology for the common public, if it can be developed further. What do I mean by common public? As you noticed, solar energy usage has increased and expanded especially in western countries, in Europe, in America, even in residential buildings. For example, I worked in the Netherlands, in France and I always saw solar panels on the houses. They would harvest sunlight through those panels and try to generate energy from it and use that energy. Could it be used in industrial areas? Possibly, but it is targeted mostly for residential areas. We at least want cheap solar cells that can be used for each house to produce electricity … So residential areas are targeted, in industrial areas, for example they can dispose of heavy metals easily. But let's say, solar panels at your home broke. Where are you going to throw the lead? It is not that simple. Our main goal is to be pioneers, to produce, to develop eco-friendly solar cells that our people can use for streets, for their houses.

Dilruba Haliloğlu: [00:05:39]. Thank you very much. You've explained it a bit already, obviously, that how important your project is for sustainability. We are facing problems because of fossil fuels, like gasoline prices. Could you talk a little bit more about how important solar energy is, how important your project is for sustainability?

Caner Ünlü: [00:05:59] Of course, let me talk a little bit about that subject right away. The sun, I mean the sunlight, is the most free-of-charge energy source for us. It is the most sustainable source that will be an energy source for millions and billions of years and will constantly warm us. While it is possible to use this resource easily and accessing this resource is actually not that difficult, the use of fossil-based sources, especially gasoline or such fuels, seems to have more impactful causes, or rather results, in nature. Let's start with carbon dioxide emission, which seems to be the simplest, but actually one of the most important things. The carbon dioxide emission and the resulting greenhouse effect. These problems can potentially put us in a lot of trouble economically. Not every country has an equal share of sources, like oil or this fossil-based fuel. It may be too much on one side and less on the other. Solar energy can help our country economically. And of course, sustainability wise, one of the most important things in the world right now is sustainability, using environmental and nature-friendly resources. Considering that the sun is the source of nature, it is one of our most important and fundamental tasks to use the sun as human beings. And it is also our task to use the sun in a way that is friendly to our environment. It goes back to the same topic. Instead of using heavy metals, we use what we get from the environment and produce solar cells. We produce materials with this kind of production mentality: more sustainable, more environmentally friendly, but also more accessible. Perhaps one of the biggest problems in the world right now is accessibility. Everyone is trying to access something. But, for example, we are now having a hard time accessing gasoline, whether it's the price or the lack of resources. But the sun on the other hand, the Sun, even if you don't reach out to the sun, the sun will reach you. In other words, it is an energy source that constantly illuminates and warms the world. In short, that's it.

Dilruba Haliloğlu: [00:08:39] Did you make any changes or have to come up with other technological solutions because of the risks that you encountered during the project? If it is not confidential, we would be happy if you could tell us about them.

Caner Ünlü: [00:08:53] Of course. Were there any problems? Of course, there were. It is really hard to start a project, perfectly execute and finish it. Whether you like it or not there will be some problems. Our biggest problem was that, although we tried to avoid those heavy metals, heavy metal salts, or these chalcogenides, the materials we use are not as effective as them. At some point efficiency becomes a big problem, they do not work efficiently. Then at one side there are solar cells that can generate 3 units of energy from 10 units of energy, while our model could produce 1.5 units of energy from 10 units. And what did we do to solve this problem? At that point we had to consider some composite materials instead of materials that are solely carbon-based. For example, we tried carbon-nitrogen composites instead of purely carbon-based materials. Then, theorising that boron could help with electron and energy transfer, we decided to add boron to carbon-nitrogen composite. Our starting point was purely carbon-based materials but when carbon itself was not enough, we doped carbon with materials like nitrogen, sulphur, phosphor, boron, materials that can still be considered eco-friendly. This was our first problem, the second one was durability. 10 minutes after you make a solar cell, you cannot go like Ohh I broke the solar cell. So, you have to buy and use it. So, what should you do to use solar cells, to make them durable? You have to produce more stabilised things. And in order to produce more stable materials, again instead of starting to look at carbon, we started to look for different tissues, polymeric tissues, that will cover and protect it. This was another concern. What else can we say … But these factors can be tolerated when compared to benefits. For example, the price. As I've mentioned, we use citric acid and urea while producing the carbon-based nanoparticles. For example, if you use citric acid and urea, you spend 0.5 units of money while you spend 20 units of money for solar cells with heavy metals. That means that you can renew the solar cells frequently if it breaks, it will still be cheaper than using heavy metals. This means that even if it is 5 times less durable, renewed 5 times, you still spend less than half of the money required for solar cells with heavy metals, this is economically more profitable. When you need to dispose of a broken solar cell, it can decompose in nature, so it is recyclable. All in all, even if there were some issues, we tried to come up with ways to compensate them. These were the obstacles that we had to overcome, and we were able to show that our project is feasible by approaching these issues from different perspectives.

Dilruba Haliloğlu: [00:12:47] Could you tell us more about the type of precautions you take in the lab? You've already said that not all materials you use in the lab are safe, some are risky.

Caner Ünlü: [00:13:02] Of course. For us, the riskiest material that we use during production is solvents generally. We tried to generally use water as a solvent, distilled water, and we did not use chlorobenzene, but we used a similar solvent, toluene, we usually used toluene. Toluene is a solvent that is considered a little harmful to our health. How did we overcome this? First of all, we had to protect ourselves very well. So, we took every precaution. We put on our glasses, we put on our masks. We said never, never enter the laboratory without gloves. We've got all the essentials when entering a lab. At the same time, we have adapted our working environment accordingly. What does this mean? For example, a toxic gas is released in the environment while we were working with toluene or sulfuric hydrogen sulphide, something like sulphur. We worked in systems that could take that gas, which we call fume cupboards, neutralise or remove it from the lab environment. In this way, we first protected ourselves. When we collected our waste, we did not throw it out to trash like that. There are certain waste collection places. There are chemical waste areas, we dumped it there. In this way, we have protected both ourselves and the environment as much as we can. What can I say other than that? And we tried to work in a clean room as much as possible. We worked in a dust-free, clean room, in certain special rooms that were not exposed to any external contamination and minimised our chances of contamination in any way.

Dilruba Haliloğlu: [00:15:02] What is the future of nanotechnology and solar panels, in your opinion?

Caner Ünlü: [00:15:11] The applications, or let's rather say the production of nanotechnology began in the 50's, 60's, and soon the applications followed it. The solar cells were not considered that much at the time, regarding nanotechnology. Why? Because there was a certain system and that system was still in development and so it was somewhat sidelined. But in recent years, it resurfaced, especially with the development of photonic materials, nano-sized photonic materials. For example, perovskite materials that contain lead are used in the production of solar cells. Lead containing material is used. What we call perovskite is a special material that is a key element, or not element, I should say key component in the production of effective solar cells. When you produce perovskites in nanoscale, you can observe an increase in the efficiency and the energy generation. The key point is this, nanotechnology has recently started to progress. In other words, although we are studying these, it is our first time producing and using some materials. That's why, in the future it will be impossible to think of solar cells without using nanotechnology. I think this is certain, somehow nanotechnology will be a component of solar cells, it will definitely be used. Consequently, I think that more effective, more environmental, more humanitarian and easier to use solar cells will be available.

Dilruba Haliloğlu: [00:17:05] Thank you, that was all of our questions. Thank you again for joining this meeting and aiding us in our project.

Caner Ünlü: [00:17:14] Thank you Dilruba, thank you too Kaan, thank you for joining. Maybe you know, I am a Bilkent graduate. I graduated from Bilkent University in 2006 … I am one of those 2006 January, 2005-2006 graduates. When I occasionally visit, I see that the campus environment is still almost maintained. Bilkent is a very good university in terms of sustainability. Treasure your university. I am sure that you will learn a lot, I have learned a lot too. Well then, guys, if it is not a problem, I should go to my next meeting. Take care and see you soon. If anything happens, we'll keep in touch, Dilruba. I will try to help you again.

Dilruba Haliloğlu: [00:17:58] Thank you sir, have a nice day.

9. Credits

Dilruba Sultan Haliloğlu found connections with the professors and conducted all of the interviews. She translated the three interviews. She found alternative and academic sources for the term project. She wrote the history, sustainability and some parts of the analysis and conclusion. She also edited the text.

Kerem Fidan transcribed the three interviews to Turkish. He found alternative and academic sources for the term project. He wrote the introduction and the theory parts of the paper. He also edited the text and citations.

İlknur Yılmaz conducted the Levent Trabzon interview. She found alternative and academic sources for the term project. She wrote about the safety and risks in the background research and findings section. She created tables for background research and findings to classificate the information and aspects.

Kaan Keven took part in the Caner Ünlü interview. He worked on the coding of interviews. He did background research on the technical aspects of solar cells and panels, nanotechnology and quantum dots. He also created the technical aspects table in the findings section.

Ece Teker conducted the Levent Trabzon interview. She found alternative and academic sources for the term project. She wrote about applications in the background research, findings. She also wrote some parts of the analysis and conclusion. She also edited the text in a minor way.