The Development and Implementation of Agrivoltaic Systems Internationally

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Abstract

Agrivoltaics was first developed in the 1980s and first began being used around 2004 with the purpose of combining agricultural activity and solar energy generation. Between 2015 and 2024, the world witnessed an increase in the development of renewable energy sources like solar energy, as well as an increase in the need to solve land use disputes, preserve the health and soil quality of thousands of acres of land, diversify revenue sources, and in some cases increase crop yields and ecological benefits to land within agriculture (Ballard et al., 2023). Agrivoltaics has been studied extensively in terms of technical aspects, and is helpful for increased crop yield, reduced water evaporation and soil preservation, lower temperatures, diversified income and off-set prosecution costs. The purpose of this study is to analyze agrivoltaic development within specific countries of the world and identify factors related to governmental and structural aspects that affect implementation. In order to do this, I analyzed agriculture data as well as renewable energy and solar energy development, overlaying them and looking for areas where there is both high crop productivity and high solar energy generation. Within this analysis, three countries were chosen as case studies for analysis: Germany, Thailand, and Chile. Research was done on government and structural policy to explain why and how agricultural and solar development occurred, and how agrivoltaics has or has not developed as another form of renewable energy. Eleven factors affecting implementation of agrivoltaics were identified, including factors relating to investment and government financial support, electricity generation and forms of renewable energy, and various aspects of agricultural structure and climate change effects. Many of the factors affecting these countries and worldwide vary according to governmental structure and geographic and regional location, and there is still much to be studied and understood about the benefits and viability of implementation of agrivoltaics.

Introduction

There has been a rise in research attributed to a system known as agrivoltaics over the last five to ten years, which most simply involves Agrivoltaics is the practice of producing both electricity and food or agricultural products on the same land. The rates of development for both solar energy and agricultural production have continuously seen increases worldwide to support a growing demand for renewable energy and food resources. In this thesis, I utilize data on solar installations and agricultural production across the globe from 2015 to 2024 to identify where solar is utilized alongside successful agricultural production. Picking cases of countries to study based on this data, I evaluate potential drivers and barriers to agrivoltaic implementation. This system is dependent on many things, including weather, crop type, financial security, and even farm size. Story of development of renewable energy, agricultural strength, and even existing agrivoltaic research facilities, creates a better understanding of what has worked in terms of implementation and what continues to hold back producers and countries from implementation. Agrivoltaics is a possible solution to the issues faced in the world today, including limited space, climate change effects, growing population, and growing demands for food and energy. Despite all of the technical information around agrivoltaics and both solar and agricultural technology, research still needs to be done on what serves to encourage or inhibit implementation of renewable energy systems like agrivoltaics.

Rationale

Although it is still a relatively new concept, Agrivoltaics was first introduced in 1981 by German scientists Armin Zastrow and Adolf Goetzberger, then first began being used in Japan in 2004 (McLeish, 2023). There are several different versions including pairing solar with livestock for grazing, pollinator plants, greenhouses, hydroponics, and crop production (Ballard et al., 2023). For the purpose of this study, I will be looking solely at pairing solar with crop production. The intentions of this system vary with the needs of individual regions since it is a factor dependent system, but for the most part Agrivoltaic systems can solve land use disputes, preserve the health and soil quality of thousands of acres of land, diversify revenue sources, and in some cases increase crop yields and ecological benefits to land (Ballard et al., 2023).

Solar Energy Development and Drivers

Solar energy, and photovoltaics in particular, is generally considered a top contender for greening the world energy system (T. Ballard et al., 2023). Between 2015 and 2024, there has been a depth of research into the development in solar energy specifically. The use of solar panels, or PV systems, has increased exponentially over the past decade and behind its success is the introduction of supportive policies, the lowering costs of solar panels, as well as increased international collaboration and investment (Solar Energy Industries Association, 2025). In 2022 alone, the world saw a 270 terawatt hours (TWh) increase in solar energy production, which was a 26% rise from the previous year, and marked 2022 as a year where the world added "more new solar capacity than all other energy sources for electricity combined" (International Energy Forum, 2024). In many ways, the structural support of a country is key to supporting the production of these systems, including government incentives, guaranteed grid access, feed-in tariffs for purchasing and production, and subsidies, which has increased solar use by around 25-30% (Shimbun, 2025). As of 2019, the world accounts that PV systems make up around 55% of renewable energy systems, making PV generally a top contender for greening the world energy system as opposed to other systems like hydro, geothermal, or wind (T. Ballard et al., 2023). Others also suggest that this system is more versatile than other renewable energy systems, in terms of weather, climate, and location. Researchers and renewable energy supporters seem to agree that solar energy will be one of the most reliable renewable energy systems in terms of allowing us to reduce greenhouse gas production and moving us towards energy self-sufficient models (Enel Green Power, n.d.).

Many countries are looking to reach net zero emissions by 2050, and solar energy has proven to be a big part of this, but it involves enormous amounts of land space that threatens the space used for agricultural and residential spaces (Just Energy, 2023). Because of the net zero emission initiative, which began in 2015 with the Paris Agreement, there has been increased interest in a variety of renewable and clean energy systems, in order to 'green' the grid (United

Nations, n.d.).[1] A decreased dependence on Russian oil and gas production in recent years has also contributed to a rise in the solar industry (Myllyvirta, 2023). Furthermore, the use of solar panels is expected to surpass wind and hydroelectric systems by as early as 2029, both of which currently dominate electric generation (International Solar Energy Society, 2024).

Agricultural Land Use and Growth

Agriculture and crop production has seen steady increases for the past several decades beginning around the 1960s, coupled with a 2.6% increase in population (Fuglie et al., 2024). However, while the rate of agriculture has been increasing each year, that percentage has shrunk at the same time, so instead of around 2% increases there is now only a 1% increase. This is due to various factors such as reduction in competitiveness, a decrease in public sector spending, a lower level of productivity, as well as disease, irrigation and water rights, emissions release, aging population and city flight. An increase in land use and crop yields is important to match growing populations and diversifying appetites and economies, and an increase in investment is important to continue to support agriculture (Ritchie et al., n.d.). The agricultural market shifts with demands for food, technology, climate change, and policy changes (Fuglie et al., 2024). There has been a noticeable shift to agricultural production to the tropical global south, accounting for around 70% of global production as of 2020, whereas in the 1960s and 1970s agricultural production was evenly distributed between the global north and south. Tropical areas have seen vast increases because of their biodiversity and carbon-rich environment (Arnfield, 2025).

Large reductions in agricultural activity have been seen in arid and temperate regions, such as in the Middle East, Africa, and central Asia which are characterized by scarce precipitation, high temperature range between day and night, and high solar radiation (Sposob, 2025), and Western Europe which lacks extreme temperature and is where the majority of the world population resides (Wikipedia, 2025). Across the Global South, agricultural land use expanded by 597 million hectares and shrank in the Global North by 260 million hectares"

[1] When considering the vast agricultural footprint, if just 1% of cropland is converted to agrivoltaics systems, this could significantly offset global use of carbon-based energy sources (Adeh et al., 2019)

according to the USDA (Fuglie et al., 2024). This suggests, and is critical to understand the successes of agrivoltaics, that biodiversity and climate zones are an important consideration factor for growth and implementation of Agrivoltaics (Arnfield, 2025). Because of the continued need for land for agriculture and energy development, agrivoltaics provides a potential avenue for co-development and a system that addresses concerns with climate change effects, reduced agriculture, and shifting policy and attitudes towards agriculture.

Agrivoltaics: Mixed Land Use

With both of these sectors competing for land, one solution could involve implementing Agrivoltaic systems. Here, I focus on crop growth as a subarea of agrivoltaics, which presents the opportunity for greening energy systems while mitigating challenges of land usage, especially in countries with little room to continue to expand with either solar farms or agricultural activity. Ideally, agrivoltaics can be used to address the growing need for clean energy while allowing increased food production for an increasing world population, and address land use disputes.[2]

Agrivoltaic systems provide potential advantages to both crop yield and solar technology advancement. Similar to wind power, agrivoltaics poses a unique advantage for its dual use of land area but is separate from other renewable energy systems in its potential for increased agricultural productivity and productive crop yields (R.K. Chopdar et al., 2024). Factors that lead to increasing crop yields, such as reduced water evaporation, lower temperatures for both microclimates under panels and surrounding ambient temperatures, reduced irrigation requirements, and stronger, healthier soil structure, have all been seen within Agrivoltaic system

[2] Other forms of renewable energy, some more widely known to the public or more commonly used, such as hydroelectric dams or wind turbines, also contribute to greening energy systems and addressing various climate change concerns. Hydroelectric power is less dependent on weather and seasons, because it is able to store large amounts of water and creates a 'water bank' that surrounding communities can draw from in times of need. However, hydroelectric is also highly location-dependent driven, with its installation depending on the water cycle and access to water, which some countries and regions of the world do not have. Hydroelectric is also known for damaging the surrounding environment during and after its installation (Lai, 2023). Wind power, another well-known source of renewable energy, especially in the midwest and sometimes out here in Colorado, can be found in rural or agricultural areas and can be paired with ranches and farms or island communities, giving it its similarities to agrivoltaics. But wind power also has its disadvantages of being dependent on weather as well as being farther from population centers and therefore having difficulty connecting with the grid (U.S. Department of Energy, n.d.). All of this is to say that there are multiple ways of achieving clean energy, with their own setbacks and advantages, and agrivoltaics is just one of the many ways of doing so.

experiments and results (R.K. Chopdar et al., 2024). Agrivoltaics is known to be multi-use and very versatile in its placement, although dependent on crop type, climate zone, investment and infrastructure, creating not only land use efficiency and renewable energy, but also diversifying income and saving money for producers, especially in remote locations (R.K. Chopdar et al., 2024).

As discussed above with agriculture production and the climate related challenges that it faces in arid and temperate regions of the world, research has shown that agrivoltaics will be of most benefit in those regions. The systems are designed to generate microclimate conditions under panels, meaning reduced temperature stress for crops and lower temperatures in the surrounding area that leads to increased power output efficiency for the PV panels, and also promotes water use efficiency (T. Ballard et al., 2023)[3]. Because most growth in agriculture is occurring in warm, tropical countries that experience higher solar radiation, agrivoltaics can potentially increase productivity by protecting crops from harsh weather and higher temperatures, while also promoting water use efficiency for majority rainfed fields. Agrivoltaics is a co-generative design and with the microclimate that it creates, it will lead to better power output, especially in warmer months and in hotter regions of the world where it is becoming more difficult to achieve positive crop yields.

Investment and accessibility will likely be an important factor in making agrivoltaics a reasonable and successful system (T. Ballard et al., 2023). Given existing patterns of installations, we can already begin to understand the structural factors that can support or inhibit adoption. Despite all that is already known about agrivoltaics, including its benefits and the setbacks it faces on the technical side, and how it could be a renewable energy system that helps usher the world into a new era of green energy, there are still barriers to implementation and development of these systems. In this paper, I evaluate what governance pathways and structural factors exist that prevent or encourage actual agrivoltaic implementation. While there is not a clearly defined ‘knowledge gap’ per say, a lot of what is not fully known is where and with what this system can truly work (Gomez-Casanovas, 2023), making it dependent on a variety of factors.

[3] This is important for arid climates with low levels of water available for irrigation.

Governance and Structural Drivers: State of Knowledge

One of the main factors of implementation of not just agrivoltaics but renewable energy systems and technology in general is feed-in tariffs [FiTs], subsidies, and other forms of governmental financial support. FiTs aim to make renewable energy more financially attractive to investors and producers by offering energy producers a guaranteed, above-market price for the electricity they supply to the grid (Kelton, 2025). Government financial assistance, the different types of incentives, and the evolution of these are important to implementation. Agrivoltaics is a system that has a major initial investment, and influences the profitability and viability of farms (Sullivan, 2024). Economic size is especially important in terms of project scale and regional differences, as both have associated benefits with cost and viability (Macknick et al., 2022).

International and/or national climate-based promises or pledges can also matter for development of renewable energy, and specifically agrivoltaics, by putting timeline goals in writing and promoting policy adaptation. The biggest international climate pledge to date is the Paris Climate Agreement, which fosters cooperation between nations on a number of issues related to renewable energy implementation and is important in this study and to agrivoltaic implementation, including finance, technology, and capacity-building between developed and developing countries. All involved countries report information and progress to an enhanced transparency framework [ETF] (United Nations Climate Change, n.d.). Aside from international agreements, countries such as Chile have also set national-level climate promises such as the renewable energy target (Climate Nexus, 2019). This evidence supports further commitment to renewable energy and climate change mitigation, and to creating reliable and cost-effective legal avenues for transition and suggests that this country and others like it have the potential to be successful in agrivoltaic implementation. Electricity generation and a country's share of renewable energy in the energy mix are also used in this study as evidence of how development and meeting these pledges has gone and how seriously countries are willing to take their promise, using International Energy Agency data (International Energy Agency, 2025).

Another structural factor that could influence agrivoltaic implementation is the agricultural sector of a country and the types of crops that are being grown and commercialized or not. The type of crops that are paired with an agrivoltaic system are an important consideration, not only in terms of if it can help a country decrease food scarcity for main crops or address land use concerns, but because there is general technical information available of what works and what does not which could encourage or bar feasibility. There are certain crops that are not compatible with Agrivoltaics, or are region dependent, so crop type does matter in terms of feasibility. Along with this, the ways in which farming in countries has developed and large versus small farm ownership may matter as a structural consideration. Some countries have adapted well to large farming operations and commercialization, especially those who are top exporters of a certain crop, which overall increases efficiency, crop yields, and wealth, and lowers costs of equipment and public consumption (Bloom Ranch of Acton, n.d.). However, many other countries still operate with a majority of smaller-scale, family-owned farms and a culture of subsistence farming. The size and capabilities of farms affects access to resources, crop efficiency, and knowledge surrounding systems such as agrivoltaics (Solar Energy Technologies Office, 2023).

Research Question

What are barriers and governmental or structural pathways that prevent or encourage agrivoltaic implementation?

Methods

In this paper, I utilized data describing agricultural production and locations of known solar farm locations and renewable power [GW] production to first identify countries with high and low rates of potential agrivoltaic installations given their climate and economic characteristics. These data portals include the GAEZ Data Portal provided by the Food and Agricultural Organization of the United Nations (Food and Agricultural Organization of the United Nations, n.d.), the Global Land Analysis & Discovery [GLAD] map on Global Cropland Expansion in the 21st century (Potapov et al., 2021), and a global solar power tracker map provided by the Global Energy Monitor (Global Energy Monitor, 2025). Using RStudio, I extracted the location of solar installations in countries that had high, medium, low and no agricultural production at the point location of the solar installation. Using the Köppen climate classification system, I identified where on the globe countries fall in terms of climate regions, and using known data on which regions are most suitable for agrivoltaics, I narrowed my search to the regions with the most statistical and evidence-based potential, chiefly being tropical and temperate regions that cover a large space near the equator and around the global north and south (Arnfield, 2025). However, there is also room for analysis on other regions, such as in Chile where there are arid, temperate, and tropical regions. Arid regions have been the most impacted by climate change effects and could stand to benefit more from agrivoltaics system benefits such as water retention, plant protection, and increased crop yield (Sturchio et al., 2024).

For each country, I conducted in-depth case research using multiple sources such as news reports, databases of agricultural characteristics, academic articles, and government reports to identify the role of structural factors in each country, which can all be found within the appendix. I developed a set of variables necessary to understand across countries in order to identify structural barriers and opportunities. These variables are listed below:

1. Country Standing
2. Renewable Energy Development
3. Farm Type and Ag Development
4. Number of Systems*
5. Alternative Power Sourcing
6. Arable Land
7. Productivity Reputation
8. Crop Types
9. Climate Zone
10. GDP Size and Sectors
11. Results from R Studio on a range of 1-3 based on ag production*

* R Studio Results: this is an independently created data set using R Studio to overlay high agricultural production and known solar use or solar farms using the global solar power tracker, google earth engine, and known agricultural productivity data.

* Number of Systems: the known or predicted number of solar systems, divided by operating, proposed, in-construction, and pre-construction, as well as any that have been cancelled or shelved.

Using the methods I stated above, I chose three countries that fit the needs and expectations of this study and are capable of agrivoltaics for several different reasons, which can be located within the appendices[4]. Based on the results of these countries, I analyzed the structural and governmental factors and pathways side to find any potential supportive or inhibiting structures to the implementation of agrivoltaics.

The first country I chose was Germany[5]. Germany was selected as a highly productive agricultural, economic, and energy generative country with a history of successful renewable energy production and large number of agrivoltaic systems established between 2015 and the present. Germany is located within a temperate region and can serve as a study of the entire region. Germany also has a dominant economy not only in Europe, being one of the largest agricultural producers and service exporters, but within the world as the third largest economy. Germany also has a solid commitment to renewable energy, both internationally and nationally, and continues to grow its share of renewable energy in its energy generation, surpassing fossil fuels a couple of years ago. Finally, Germany was chosen based on its RStudio results and the highest level of agricultural and solar energy found within the data.

Then, I selected Thailand for this study because of its role in Asian governments and its historical record, as well as its high productivity in agricultural and solar activity, as well as developmental proof of supportive renewable energy policy, is why it is a selected country for this study[6]. Thailand has a topical environment that promotes healthy soil and agricultural development, and contributes to its 8% agricultural sector of GDP. In Thailand, rice and other crops that are compatible with agrivoltaics are grown such as fruits and root crops, which affect implementation and feasibility. Thailand has also recently been classified as a newly industrialized country, yet at the same time as all of this has no agrivoltaic development or plans for development which makes it an interesting case for barriers.

Finally, I selected Chile for this study because of investment and development in renewable energy as well as climate change precautions, especially when compared to other South American countries[7]. Chile has established a few agrivoltaic research facilities which study the compatibility with different local crops and cherry trees. This is important for implementation because Chile is a top fruit producer and exporter, and many fruits are compatible with agrivoltaic systems. Chile experiences over a dozen different climate zones,

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[4] See 'Appendix A through C' all sections
[5] See 'Appendix A' sections A1-A4
[6] See 'Appendix B' sections B1-B4
[7] See 'Appendix C' sections C1-C4

making it a diverse country for several different crops and other agricultural activities, especially in the Central Valley region, and this contributes to its respectable agricultural sector of GDP. Chile has the largest portion of renewable energy out of the total energy generation at 70% through national climate pledges, and has a growing portion of solar energy within this mix, displaying a commitment to renewables and system development.

Agrivoltaics, a system pairing solar energy with agriculture and specifically with crop production, can be a possible solution to many of the problems that the world faces today and can provide several benefits to energy and agriculture producers if implemented. This system is very dependent on a variety of factors, and what might work in one place cannot be feasible in another part of the world. Using the methods I highlighted above, I selected eleven factors[8] that had the most impact across all three case study countries in terms of implementation and the aids and barriers that countries face when implementing new renewable and co-generative systems.

Results

For each of my three countries, Germany[9], Thailand[10], and Chile[11]I provide in depth case studies of their renewable energy and agricultural development, as well as agrivoltaic implementation and viability. Here, I focus on common findings and lessons across the set of case studies relating to agrivoltaics development and implementation.

In Table 1, I summarize factors that inhibit or encourage implementation of agrivoltaics and suggest whether implementation is or is not dependent on these factors within the country. Dependance means that something about these factors creates opportunity or a barrier for implementation, and could be something to consider as this system is dependent on many things in different regions of the world. Factors that inhibit implementation are highlighted in red within a country, and those that encourage implementation are highlighted in green. Factors that have the greatest effects on implementation stood out the most within my research are highlighted in yellow under potential drivers/barriers.

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[8] The eleven factors are highlighted in depth in 'Appendix D'
[9] See 'Appendix A'
[10] See 'Appendix B'
[11] See 'Appendix C'

Table 1: Drivers and Barriers to Agrivoltaic Implementation Internationally (Appendix D)[12]

Potential Drivers/Barriers	Description	Germany	Thailand	Chile
Feed-in Tariffs (FiTs) and Other Government Support Systems	Adoption and adaption of legal and governmental policies and lands over time to encourage development	Encourage	Encourage	Encourage
Size of Economy and Agricultural Sector	Dedication to agriculture in GDP to supply resources for agrivoltaics	Inhibit	Encourage	Encourage
Renewable Energy Development	The rate of development of solar energy, and agrivoltaic research facilities and farms to indicate a desire to implement such systems	Encourage	Inhibit	Inhibit
International and National Climate-Based Pledges	Evolution of national and international pledges to increase renewable energy use and cut emissions displays development	Encourage	Encourage	Encourage
Climate Change Impact	Effects of climate change have an impact on agricultural production and solar energy efficiency and increase need for protection	Encourage	Encourage	Encourage
Crop Type	Crop compatibility with Agrivoltaics and the crop production of countries locally and commercially	Inhibit	Encourage	Encourage
Farm Size and Designation	Small family-owned farms and commercialized or large farms and the profitability and resources available for implementation	Encourage	Inhibit	Encourage
Investment and Grid Access	The amount of current investment which encourages development and upgraded grid access versus incoming investment or lack thereof	Encourage	Inhibit	Inhibit
Electricity Generation and Alternative Power Sourcing	Total electricity generation and the share of renewables which indicates room for development	Encourage	Encourage	Encourage
Use of and Threats to Renewable Energy	Different forms of renewable energy that countries depend on affected by climate change and likelihood of solar energy development	Encourage	Inhibit	Encourage
Currently Operating Solar Projects and RStudio Productivity	The amount solar projects, including operating, in-construction, and cancelled, and solar and agricultural production from RStudio data	Encourage	Encourage	Inhibit

[12] See 'Appendix D' for an expanded table that was used to create this table

Feed-In Tariffs [FITs] and Other Government Support Systems

One of the main ways that countries have been encouraging the development of renewable energy systems is through government financial assistance, like tax breaks, subsidies, and feed-in-tariffs [FITs]. All three countries have introduced one or more types of incentive based financial support to encourage producers, citizens, and farmers to buy and install renewable energy systems. Through these financial assistance programs, energy producers are guaranteed things like grid-access and above-market prices for the electricity that they supply to the power grid (Kenton, 2025). These countries know that investing and purchasing renewable energy systems as initially very expensive, but also that the long-term benefits such as lower costs, clean energy, and better access to energy will outweigh the cost and so they offer these incentives (Stokes, 2013). Promoting financial incentives also displays a commitment and interest to renewable energy growth. Germany had a Electricity Feed-In Act that involved fixed tariff rates to make it easier to introduce renewable energy to the power grid. This act served as a precursor to the 2000 Renewable Energy Sources Act [EEG] which set up a legal avenue for the transition to renewable energy and introduced higher feed-in fees for solar energy. This law was revised in 2012 amid concerns of rising costs and burdens to the industry, so they pivoted to cost-effectiveness and reliability at the center of the energy transition (Deutschland.de, 2014).

Thailand introduced their own feed-in policy in 2007 called the Adder premium policy. It was intended to provide financial support to smaller sized producers and help them invest in renewable energy without as many financial hurdles. The goal of this tariff was to stimulate the private sector to participate in renewable energy generation (Solar Magazine n.d.). Chile has introduced many financial incentives for renewable energy, such as tax credits for research and corporations that have reductions from 27% to 25%, with the introduction of a 2% tax that can be deducted through investments in high-tech equipment (Rodríguez-Villate, 2024). Furthermore, in 2025, Chile worked with the European Investment Bank (EIB) to secure a $110 million loan to finance energy efficiency and renewable energy investments for small and medium businesses and encourage growth (European Investment Bank, 2025). And speaking of investment, tackling the large initial amount required to implement this system, investment amounts and improvement of the energy grid is an important factor that affects success and development.

Investment Initiatives and Grid Access

Investment and grid access is perhaps the most critical part of encouraging implementation, because without solid grid access there is no guarantee of a profit and there is no generation of renewable energy supplying the country. Currently grid access is unreliable in many countries, and helpful investment has proven to raise access to the grid.

Investment promotes adoption and development of renewable energy and also strengthens things such as energy grids and public knowledge. Investment also comes with benefits such as job creation, energy security, and economic growth (Prismecs, 2024). In Thailand, they are calling on $6.8 billion in investments before 2036 in order to create smart grids and support electricity generation (Solarbe Global, 2021). Being the leaders in renewable energy among ASEAN countries, Thailand has also attracted more than USD 10.7 billion of investment in renewable energy from 2006 to 2018 (Vakulchuk et al., 2020). Chile alone saw a 231% increase in year-on-year renewable energy investment as of 2024, which has turned out to be around $5.7 billion USD and has been used to fuel growth in solar and wind projects (Jacobo, 2025). Chile also introduced the 2016 Transmission Law to enhance the state's role in energy planning through open grid access and interconnectivity (Natorski & Solorio, 2023). German renewable power has been a large economic driver as it has lowered consumer costs, created jobs, and could save Germany billions of dollars as it moves from imported Russian oil to fully renewable energy by around 2050 (Dublino, 2024). In 2023, Germany invested $89.12 billion USD into clean technology, which was 29% of the European Union's overall investment (Zero Carbon Analytics, 2024) and has also invested around €37 billion in renewable energy systems to promote improvement of the electricity grid and build wind and solar projects (Schlick, 2024). Furthermore, Germany's Renewable Energy Act (EEG) guarantees access to the grid for renewable energy projects, promoting the growth of solar and wind power (Appunn, 2014).

Outside of financial assistance, investments, and grid access, the implementation of agrivoltaics can also be influenced by the strength of a country's agricultural sector and its development, alos meaning its share of resources and knowledge.

Size of Economy and Agricultural Sector

Renewable energy and agrivoltaic systems are a large investment for public and private sectors of any economy, which is why so many governments work to secure financial assistance and introduce incentives, as it could lead to lower costs and increased development (Macknick et al., 2022). Out of the size of a country's economy, the GDP of their agricultural sector is an important consideration because it influences the capacity to adopt and develop new systems such as agrivoltaics. Germany has the largest economy out of the three countries, with a current GDP of $4.92 trillion USD (World Bank, n.d.) and that makes it the largest economy in Europe, third largest in the world (Glunz, 2025). Out of this, Germany only contributes about 0.8% of its total GDP into the agricultural sector (World Bank, 2023). Thailand has the second largest economy out of three countries with a current GDP of $545 billion USD, and is the second largest economy in Southeast Asia (International Monetary Fund, 2024). Thailand's agricultural sector makes up a substantial 8.6% of its GDP as the world's largest rice exporter (World Bank, 2023). With a GDP size of $343.82 billion USD in 2025, Chile has the smallest economy out of the three but annually devotes around 3-4% of its total GDP to the agriculture sector, between 2015-2023, and is one of the largest fruit exporters in the world (World Bank Group, 2023). Outside of the financing available and the way in which agriculture is treated and has developed in different countries, these systems are also dependent on crop type, which can be a big factor for countries that are large exporters of certain crops like Chile and fruit.

Crop Type

Crop type and the commercialization of crops in these three countries is critical to the success and even the need of an agrivoltaic system. These systems are very crop and region dependent, and it is important to note that even with some crops that are not considered to be 'ideal' to grow in tandem with agrivoltaics, they are productive in some areas of the world and not others. With the right system modifications, many crops can be paired successfully (Orennia, 2024). An increase in crop efficiency could mean a decrease in food and/or water scarcity and the implementation of an agrivoltaic system could solve land use disputes or mismanagement. There is general technical information around what crops work and what crops do not work paired with an agrivoltaic system, because issues of shading, humidity, and solar radiation have an impact on crop productivity, water retention, and energy production. Currently, vegetables such as potatoes, carrots, tomatoes, leafy greens like lettuce and spinach, and certain fruits like berries do well under agrivoltaic conditions (Just Energy, 2023).

While crops such as cereals and fruit trees have not done as well in some areas, but have in others as seen with Chile, these two categories of crops are some of the most produced and exported around the world (Just Energy, 2023). Germany is a major producer and exporter of cereal crops and mostly important other foods. Outside of wheat, which has shown increased yields in research, cereals are not very compatible with agrivoltaics in Germany. But, other crops that can be grown in Germany such as potatoes and vegetables, which have undergone studies that reveal no or insignificant affect in yield when under solar panels (Widmer et al., 2024).

Thailand, along with most other Southeast Asian countries, produces rice as its main crop, along with wheat, maize, rubber and fruits like mangoes and tangerines. Unlike in Germany, rice has actually been proven to at least be a financially successful crop, even if there is an overall decrease in crop yield due to shade intolerance, because of the income from energy generation (Kyaw, 2023). That does however mean that sometimes this system is implemented not for crop production but for better energy generation efficiency (. But, some studies have also shown that higher temperatures had no significant impact on rice yields (Kyaw, 2023) and others noted that rice yields could decline more noticeably due to adverse effects associated with increased temperatures, including water stress (Coelho et al., 2023). So, the impact of shading from agrivoltaics on rice still has room to be studied. In Chile, while they also produce things such as wheat, corn, and oats, they are some of the top fruit producers and exporters in the world. While is the world's leading exporter of fresh cherries, prunes, and dried apples and is the second-largest exporter of fresh plums, shelled walnuts, shelled hazelnuts, raspberries, blackberries, and frozen blackberries (Malheiros, 2023). According to recent research, fruits such as pears, apples, cherries, forms of berries, and other stone fruits are suitable or can adapt to shading and partial shading conditions under agrivoltaics (Asa'a et al., 2024). Much of the world's crop, regardless of current productivity and exports, are under threat from different climate change effects and spells the need for systems such as Agrivoltaics, to protect agricultural production and investment from adverse weather and crop failure.

Climate Change Effects

Part of the reason for pushing the implementation of renewable energy systems such as agrivoltaics is to combat climate change effects, which has adverse effects on agriculture, energy production and dependability, and health of citizens. Almost all nations experience some level of climate change that affects one or more of these categories, and while this factor does not necessarily impact implementation, the system itself can impact climate change effects. While renewable energy is working to decrease the release of emissions to stop temperate increases and extreme weather, and create new and efficient energy systems, agrivoltaic implementation can be one of the solutions to protect crop productivity while also generating more clean energy.

In Chile, because of the amount of climate zones like tropical, arid, polar, and temperate that it intersects, it experiences several extreme natural disasters, such as volcanic eruptions, earthquakes, and tsunamis. With climate change, Chile is expecting to see changes in the frequency and severity of natural disasters including wildfires, floods, and droughts (Wikipedia, 2025). The changes that these conditions will bring is already having a large impact on manufacturing and agricultural activities, as well as electricity generation, food and water scarcity, and public health (Climate Change Knowledge Portal, n.d.). In Germany, they experience a temperate region where the weather is less influenced by the oceans, and they experience more temperate extremes during seasons (Met Office, n.d.). But because of climate change, Germany has begun to experience cloudy and windless winter periods, which affect solar and wind energy generation and forces them to consider investment in energy storage systems, or batteries (Schlick, 2024). Thailand is classified as a tropical climate zone meaning that the area experiences higher temperature and higher levels of rainfall (Coelho et al., 2023). But, the promise of rainfall has become increasingly unpredictable as climate change brings longer periods of drought and diseases. With this change to an already diverse and weather dependent country, Thailand could see increases in food and water insecurity, economic instability involved with its top export of rice, and a disruption to citizen’s livelihoods and income to farmers and producers (Coelho et al., 2023).

With many of these countries under threat from these effects or already experiencing them, there has been a shift in several countries towards not only more renewable energy to combat climate change, but also agrivoltaics to protect agriculture and produce more energy.

Renewable Energy Development

Many country’s renewable energy development began when the Paris Climate Agreement was adopted and put into force between 2015 and 2016, with goals to reduce greenhouse gas emissions and promote renewable energy through financial and technological support (United Nations Climate Change, n.d.). The development of solar, which has experienced several ‘booms’ in the last five years, and agrivoltaic interest becoming more common as a co-generative system speaks to the quick development of renewable energy and a desire to diversify. But as of more recently, the discussion around solar energy and agrivoltaic potential has gained traction, especially in Germany and Chile.

For Germany, the first mention of an agrivoltaic system was in a 2021 press release when the first agrivoltaic research facility was built near Lake Constance with the help of the Fraunhofer Institute for Solar Energy Systems ISE. At this facility, there were eight varieties of apples being tested with four different panel systems over a five-year period (Fraunhofer ISE, 2021). Since then, Germany has built 21 agrivoltaic facilities that have a combined capability of 81 MWh with rise to 400 MWh expected between 2023-2024 due to the changing legal environment. It has also been estimated that at the end of 2024, there were some 45 agrivoltaic facilities operating in Germany but the number in 2025 is still unclear (Pump et al., 2024).

Chile also has relatively successful implementation of agrivoltaic facilities, yet they face issues related to the projects not being fully commercialized to farmers due to its high investment cost and poor regulations around project development (Schönberger & Jung, 2022). Chile built three agrivoltaic plants in 2017 near the country's capital, Santiago de Chile, which is located within the Central Valley. Each of these plants can produce 12.48 kWp and were placed in vegetable fields within farms and had fix-mounted PV panels (Gese et al., 2019). Here, researchers are testing which plants worked with panel shading and also measured solar radiation, temperature, and humidity to determine crop yield. One of these facilities was placed in an area with connection to the electricity grid but with frequent disruptions, and it was able to provide power to seven families (Halney, 2018) and display potential for co-generative benefits. Also, in 2023, a 20 hectare 9MWh distributed-scale agrivoltaic farm, Ayla Solar, was built to work with a variety of cherry trees and determine shade tolerance (Wikipedia, 2025). Compared with Germany and small-scale development, Chile's current projects are being developed on a larger scale. Given the context of agricultural strength and solar energy development seen in appendix B, it is then a surprise that Thailand's origin of agrivoltaic development doesn't exist.

Thailand has been promoting renewable energy since 2012, and they have several hundred solar plants operating (Global Energy Monitor, n.d.). But there are only vague mentions of agrivoltaic interest starting around the 2020s, in line with worldwide interest starting to develop as well, however there is no concrete evidence that an agrivoltaic farm or research facility exists in Thailand yet. This could be due to a variety of factors including a general knowledge gap about this system, especially for those involved in agriculture in Thailand. Thailand doesn't face significant land scarcity like other countries do, yet it does suffer from inefficient land use, and agrivoltaics has been one of the systems suggested to solve land use mismanagement and diversifying long-term income for farmers (School of Renewable Energy and Smart Grid Technology & Naresuan University, n.d.).

Much of this development, as previously stated, is due to climate pledges, nationally and internationally, and these pledges mark a country's commitment to renewable energy development and create opportunities for the implementation of new systems like agrivoltaics.

International and National Climate-Based Pledges and Promises

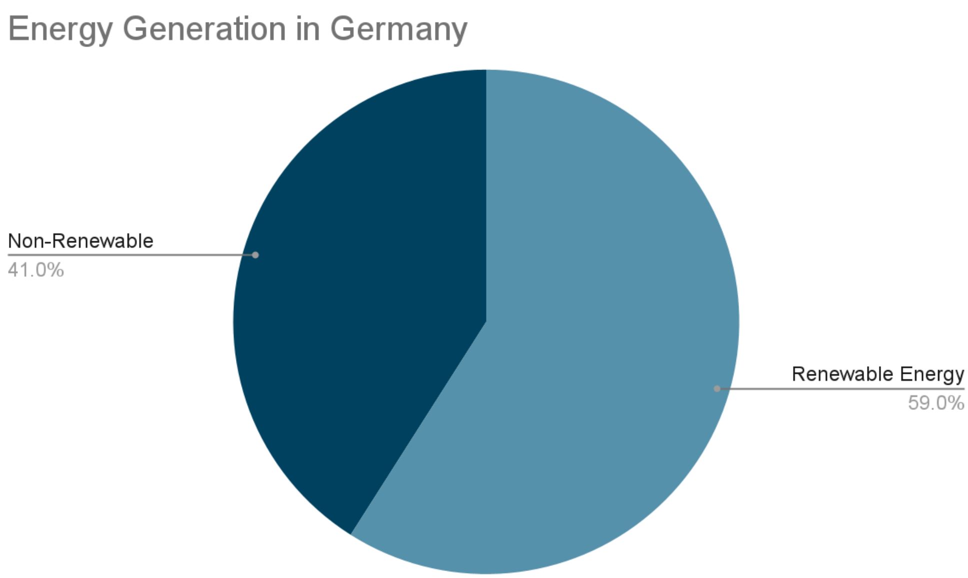
Interest in renewable energy has been going on for several centuries, with some countries developing at a faster pace than others. Climate and renewable energy-based pledges and promises, both internationally and at the national level, have become increasingly popular between 2015 and 2025, or since the adoption of the Paris Climate Agreement. Many countries including Germany, Thailand, and Chile have joined some sort of international and/or national climate-based pledge in order to advance the development of renewable energy and match or exceed the progress detailed by the Paris Climate Agreement.Chile specifically has had a very long and detailed history of renewable energy promises, beginning in 2008 when they introduced a law that set a target for renewable energy of 10% by 2025, which was revised in 2013 to 20% by 2025 (Wikipedia, 2024). Since then, the Chilean President Piñera has set the goal of 70% renewable energy by 2030, beating the Paris Climate agreement standard by 20 years (Climate Nexus, 2019) which they reached in 2024, beating the Paris Climate Agreement by decades.

In Thailand, they created The Renewable and Alternative Energy Development Plan [AEDP] in 2012 which was a decade long project to increase solar, wind, hydro, and biomass development by 25%. This plan was revised in 2015 and renamed the Alternative Energy Development Plan 2015-2036, which aims for renewable energy to comprise 30% of Thailand's total energy consumption by 2036. Also in 2018, the Power Development Plan [PDP] was produced by the Thai government to support renewable energy advancement and set clear objectives for that advancement (Lertvittayachaikul et al., 2024). Finally, in Germany, aside from being a major contributor to the Paris Climate Agreement, financially and knowledge-wise, they created the climate action plan 2050 (Cornaló, 2021). The aim of this plan is to reach net greenhouse gas neutrality by 2045, beating the Agreement by 5 years. They also have made plans to cut emissions by around 65% by 2030 and 88% by 2040, when compared to pre-industrial levels (Appunn, 2025).

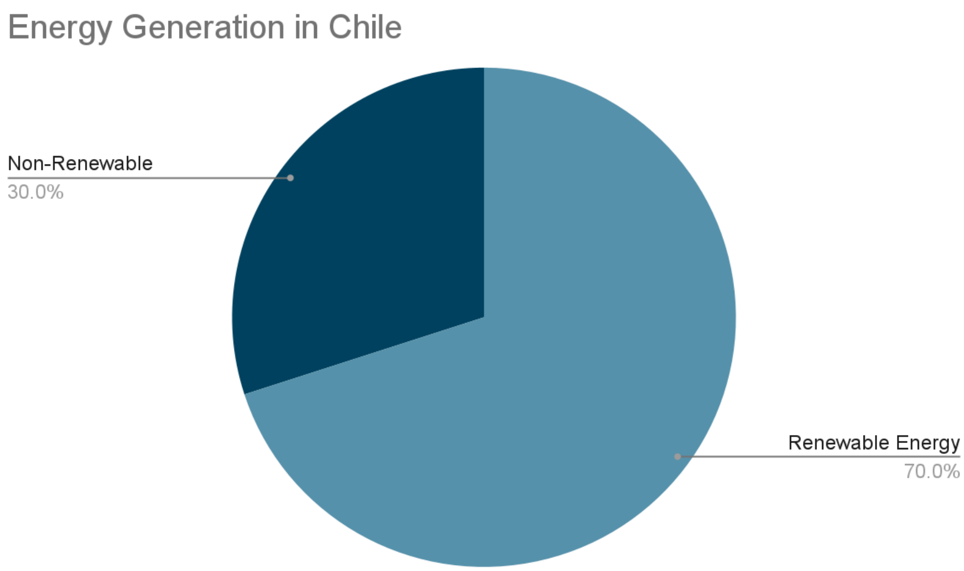
The commitments to the reduction of greenhouse gases and the development of renewable energy has been very easy to identify within a country's alternative power sourcing percentages and the electricity that it generates from various forms of renewable energy.

Total Electricity Generation and Alternative Power Sourcing

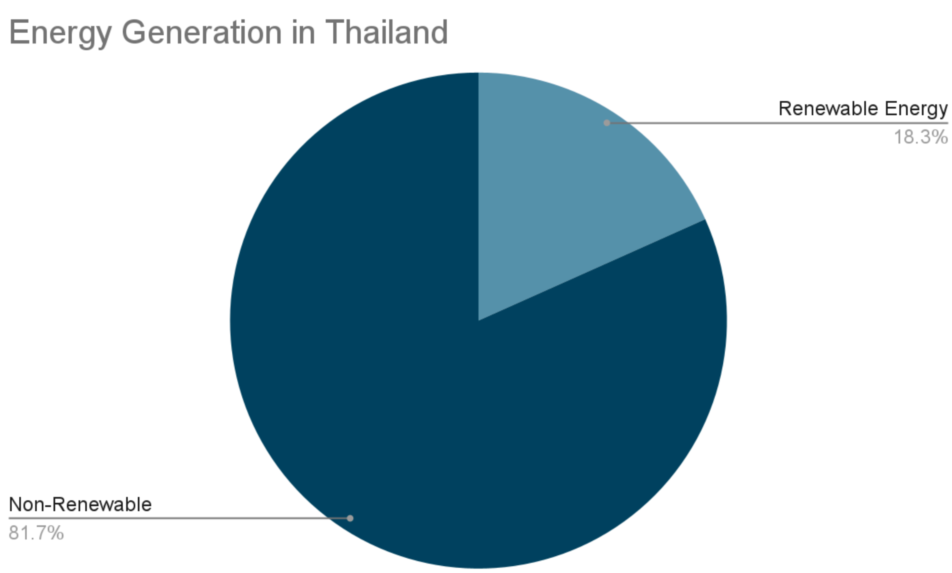
All three countries have continuously increased the share of renewable energy that contributes to the overall energy generation and signals a movement away from fossil fuels and non-renewable energy in an attempt to green energy systems in accordance with the Paris Climate Agreement and other pledges. In Germany, renewable energy generated 206 TWh between January and September of 2024 exceeds fossil fuels of 140 TWh (Rangelova and Rosslowe, 2024), and the country currently enjoys around 59% of its total energy production being produced through renewable energy (Below).



Chile also enjoys a very high percentage of their total energy production being from renewable energy sources, with a percentage of around 70% and fossil fuels being the other 30% in 2024 (Broadbent, 2025). That percent was up from 51% in 2022, marking a nearly 20% increase over two years (Statista Research Department, 2024) (Below).



Although smaller than the other two countries, Thailand also has a portion of their total energy generation that comes from renewable energy sources. In 2023, renewables made up 18.3% of their total energy (International Energy Agency, 2022) and had a capacity of 223.3 TWh (Walderich, 2024) (Below).

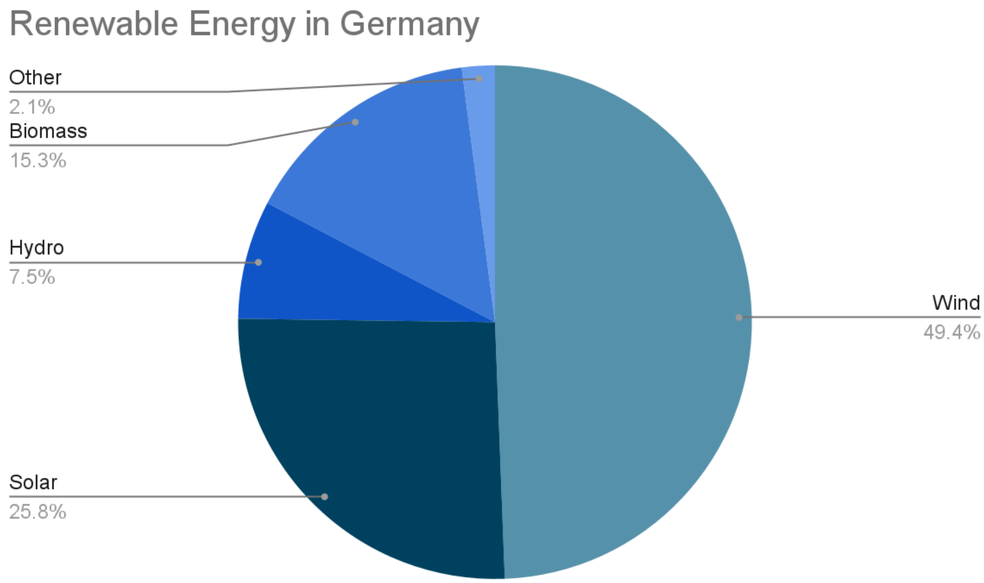


Alternative power sharing and percentages of power generation that come from renewable energy sources are good sources of data and also evidence of progress towards renewable energy goals. Electricity generation and a country's share of renewable energy in the energy mix are also used in this study as evidence of how development and meeting these pledges has gone and how seriously countries are willing to take their promise, using International Energy Agency data (International Energy Agency, 2025). Out of these percentages, it is also easier to see the share of renewable energy that comes from solar, which will be reviewed below, to understand the amount of power available for agrivoltaics and if it can develop or if there is even a reliable grid access level.

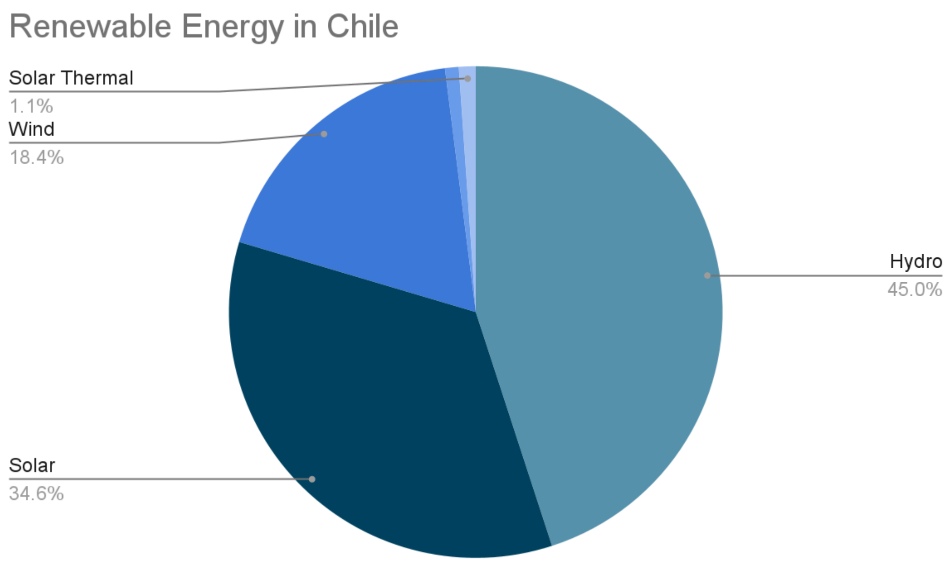
Use of and Threats to Renewable Energy

There are other forms of renewable energy systems that are more commonly used, were implemented much earlier, or are more widely known to the public in these countries. Each of these systems has their own benefits and setbacks, especially relating to environmental health, cost, and access to things such as wind and water. But each system has been implemented and introduced as renewable energy as a way of contributing to greening energy systems and addressing various climate change concerns.

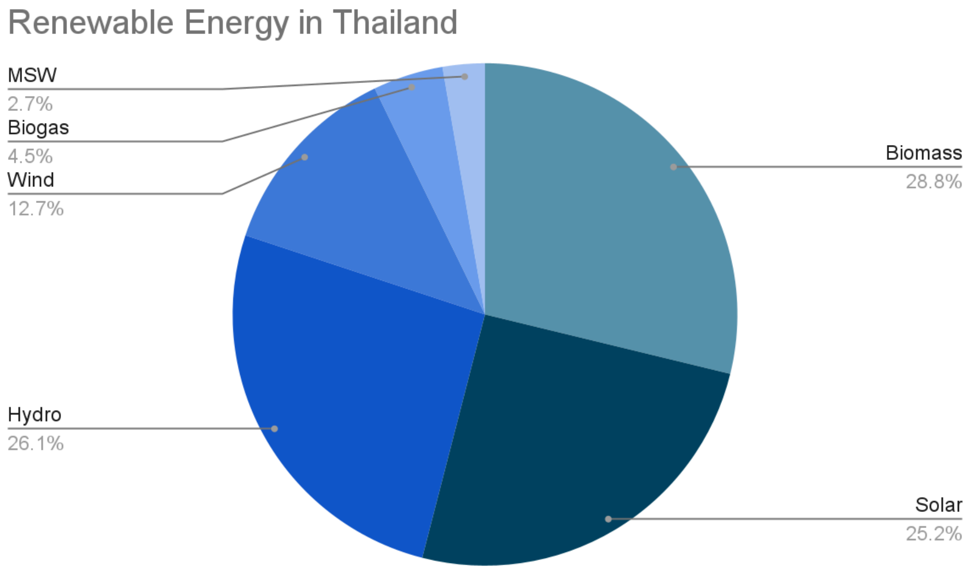
In Germany, wind power makes up the majority of their renewable energy production, approximately 28.5% of total energy production and almost half of all renewable energy and is divided into on-shore and off-shore wind energy (CleanWireEnergy, 2024). Germany has a considerable amount of land and coastline to devote to wind energy, due to its temperate climate and shared development of offshoring in the North Sea and Baltic Sea (Wehrmann, 2023). Wind energy has been quickly developing due to the Land-Based Wind Energy Strategy that Germany created in 2022 with the goal of developing a land-based wind power capacity of 160 GW by 2035 (IEA Wind TCP, 2022). However, solar energy has been growing rapidly, accounting for over a fourth of renewable energy and 14.9% of all energy produced in Germany (Clean Wire Energy, 2024) within the past two to three years as due to a number of German accelerated rollout strategies like increased remuneration, simplified grid connection for small PV systems, and raised maximum bids in solar tenders (Rangelova & Rossslowe, 2024).



Chile has a very large percentage of their renewable energy production in hydropower, approximately 45% (International Energy Agency), which is mostly due to the geography of the country and its abundant water resources. It has thousands of square kilometers of lakes and too many rivers to count (Jarroud, 2016) and in just the Cajón del Maipo valley alone, there are 41 miles of tunnels beneath the mountains that source millions of gallons of water from three rivers: the Río Volcán, the Río Yeso, and the Río Colorado, and provide electricity to the Santiago metropolitan region. However, Chile's hydropower is at risk as climate change has caused a rapid increase in melting glaciers and brought about historical droughts (Isaza & Mulkey, 2023). Because of projected decline in precipitation and streamflow due to climate change, many believe that other energy sources such as wind, solar, and geothermal could combat the loss of hydropower capacity. Solar makes up 34.6% of Chilean renewable energy, wind accounts for 18.4% and geothermal at 0.9% with a minimal amount of solar thermal energy accounted for as well (International Energy Agency, 2024).



In Thailand, there is a smaller gap between the different forms of renewable energy that it employs to make up the 18.3% share of their total energy generation (International Energy Agency, 2022). Biomass, which is the practice of turning bio-materials into other alternatives, makes up 28.8% of all renewable energy, is expected to only grow (Fitch Solutions, 2021). Thailand also has numerous rivers and lakes for generating hydroelectricity which contributes 26.1% to the total renewable energy generation (International Trade Administration, 2021). Thailand has set out on the world's largest project of a hybrid hydro-solar power plant that puts solar panels on top of some of the country's largest dams and allows for continuous power generation and the option to switch between the two (World Economic Forum, 2021). Solar energy is another large portion of Thailand's renewable energy, making up 25.2% of the total and continuing to grow (International Trade Administration, 2021). Along with the hybrid hydro-solar project, solar energy has grown due to government initiatives such as the Residential Solar Project in 2019, which allows regular residential electricity consumers to install solar panels on their rooftops, generating power for their own use (Recessary, 2023). Solar energy is also successful because of the high solar radiation and long periods of continuous sunlight in Thailand (Riverhouse, 2022).



There are certainly opportunities for implementation and the demand for renewable energy systems continues to be championed. Another consideration is where these facilities can be sited to bring the best productivity, decreased investment risk, and support producers during climate change. Along with the share of solar energy within a country and the strength of the agricultural sector, farmers and producers must be able to understand and implement these systems effectively and efficiently.

Farm Size and Designation

Throughout this research, there was a clear divide between smaller family-owned farming practices and culture, and larger-scale commercial farming activity. Agrivoltaic implementation has been known to perform better with smaller farming operations, as a means of benefiting the farmer and diversifying land use and income (Solar Energy Technologies Office, 2023). This is evidenced by the 45 facilities in Germany and the 4 in Chile, which for the most part have been sited on smaller land areas with regional crops. But, these smaller farm operations also have lower efficiency and productivity when compared to larger farms, especially in terms of increased vulnerability to crop failure (Bloom Ranch of Acton, n.d.). While smaller and family-own farms, which dominate agricultural production in these countries, have seen some benefits from this system such as increased productivity, crop protection, and diversified income, many farms around the world also experience less access to resources, especially finance-wise, and knowledge necessary to implement renewable energy systems such as Agrivoltaics.

Most of the farms in Chile are small-scale, have smaller production values, and require energy efficient technology to stay competitive (International Trade Administration, 2023). In Chile, there are also some larger scale commercial farms for more commercialized crops that employ hundreds to thousands of workers (Cooke, 2022). Regardless, the agricultural sector employs 6.32% of the country's workforce (O'Neill, 2025) and many and many producers seem open to renewable energy (World Economic Forum, 2023).

Thailand also operates small scale farms that are family-owned and generally passed down through generations. These small farms are generally one or two crop producers and have lower productivity levels (United Nations Thailand, 2020) because they are generally considered subsistence farmers as opposed to commercial farmers in rural areas and have limited resource bases for further development (Chainuvati & Athipanan, 2001). As seen here, despite sharing similar small farm characteristics to the other countries, Thailand still faces barriers through its majority subsistence culture. These farms are rural with little to no grid access yet, and have low access to resources. Also, there are currently zero operating agrivoltaic facilities, with a fairly smaller share of renewable energy around around 18%, compared to Chile nearing 70% and having helpful policy, open renewable energy markets, and currently existing agrivoltaic facilities that have been limited to the private sector to support smaller farms at this time.

Nearly half of the farms in Germany are also small, family-operated farms, and range from one to several crop producers (Ballard et al., 2023). However, many current agrivoltaic projects and greening efforts in Germany have been geared towards medium or large farms, which makes sustainability and economic viability of smaller farms at risk. Furthermore, there has been a shift in Germany towards larger operations to increase efficiently, but just in East Germany, while farms remain small and family run in Western Germany (Wuepper et al., 2020).

Farm size and other considerations for agrivoltaic implementation that have been reviewed above, such as shares of renewable energy and dependency on crop, location, and financial assistance, were researched according to the results from RStudio and other methods.

Currently Operating Solar Projects and RStudio Productivity

The results of databases like the Global Energy Monitor's global solar power tracker and from RStudio have been influential in analyzing where there are high levels of solar production and operation, as well as where we see both high solar and high agricultural activity overlapping. These results were the base for selecting countries to analyze in my case studies and have been expanded upon in the above sections in terms of renewable energy development and agricultural productivity.

In Chile[13], the results from RStudio displayed 4 2s, which means there is good agricultural production, even if it isn't considered the highest. These results are looped in with hundreds of thousands of other 2s from countries all over the world, suggesting that it is one of dozens of countries that experiences average agricultural production, and also is sited near solar farms or solar activity (Citation). Furthermore, results from the Global Energy Monitor reveal 257 operating solar farms and plants, as well as dozens more in construction or being announced. Chile also has 8 shelved projects as well as 23 cancelled projects. This is significantly more cancelled than Germany, which had zero cancelled projects, and Thailand, which had three. While not a large number when considering that Greece had around ninety cancelled projects, the United Kingdom had 76, and the United States had 338, it is still the largest of this study (Global Energy Monitor, 2025). In Chile recently, there has been a bottleneck of transmission from the grid coordinator which routinely decreases renewable supply, particularly in northern regions far from Santiago. There has also been an increase in prices and financial distress, and some legal troubles with a confusing implementation system, leading to a decrease in solar projects (Garip, 2024).

[13] See 'Appendix C Section C4'

Thailand[14] has nearly 430 solar projects that are active, along with 6 new announced projects and 1 project in construction (Global Energy Monitor, n.d.). Furthermore, from the RStudio results, there were a handful of countries that had a ranking of 3 on the R studio results, indicating high agricultural production. Thailand had 3 3s in this result set, along with 104 2s, which also equaled relatively high agriculture production, meaning that Thailand has displayed a high amount of agricultural productivity as well as high levels of solar power generation. Due to rising energy demands and an increase in government incentives such as FITs, net metering, and Corporate sustainability commitments in Thailand, the solar market and the renewable energy market are entering periods of rapid expansion in 2025, with a growth rate of 7% expected by 2029 (Sungrow, 2025). And Germany[15], along with Thailand and five other countries around the world were the only ones to show data of the highest agriculture production along with the solar data fed into R Studio. Germany almost doubled the amount of 3's as any other country, with 5 3s as well as 1,137 2s, which also equaled relatively high agriculture production. Germany has been a standard for renewable energy production for nearly a decade, with continued increases in solar projects. Currently. Germany has 6, 569 current solar projects, with around 10 more proposed and 4 under construction, as well as zero cancelled projects and eight retired solar plants (Global Energy Monitor, n.d.).

Discussion

Regardless of how similar or different Chile, Thailand, and Germany may seem, they each have something to offer in terms of solar energy and agricultural production, and all provide potential for agrivoltaic development. The focus of this research on structural and governmental frameworks also comes from my personal experiences and goals, and my desire to attend law school and study environmental, international, or a mix of both in the legal world, with a focus on renewable energy and clean energy systems such as agrivoltaics. Out of these results, I was

[14] See 'Appendix B Section B4'
[15] See 'Appendix A Section A4'

able to identify the implications associated with the governmental, legal, and structural pathways and barriers to implementation, and what the results would mean for agrivoltaic implementation.

First, I find FiTs and other government financial assistance and incentives have been key in encouraging development of renewable energy and curbing costs. While it is encouraging private sector activity, government financial assistance is also encouraging commercial development, in business and farms, which aids implementation because it gives systems like agrivoltaics the opportunity to spread to more commercial farms and influence commercialized and needed crops from these countries. Encouraging more government cooperation will be especially important to agrivoltaics because investment and interest is essential to its success, since there is still not a lot known about the success rate of every crop and in every condition around the globe, and investment might be seen as risky. From my results, it seems especially important to have FiTs and government assistance such as tax breaks, loans, and electricity policies that continue to go through revision and change as the climate and attitude surrounding renewable energy changes, because it shows trust in the outcomes and increases accessibility and understanding of the technology.

Second, I find that the size of an economy may matter so long as it enables FiTs and governmental spending. Some countries dedicate a reasonable portion of their GDP to the agricultural sector, but this also does not always mean that they have or are willing to incorporate agrivoltaic systems. The GDP dedication is more so an indication of how much room is available to expand the use of renewable energy in agrivoltaics, what resources are available, how much a country depends on agriculture and desires continued improvement, and how much a country's farmers could benefit from something such as agrivoltaics. There is somewhat of a connection between the size of an economy and the reach of renewable energy development, such with Germany having many projects and the largest GDP but also dedicating only a small portion of their economy to agriculture, suggesting that there might not be a high demand or interest for systems such as renewable energy. And in that situation, what little of the GDP is dedicated to agriculture limits expansion into more productive systems. Economic size could also not be entirely a factor, because countries like Chile have done more interest-raising of renewable energy than Thailand with $200 billion smaller GDP, and also less of a dedicated portion of GDP to the agricultural sector. So, it might not necessarily be that the larger the agricultural sector and more emphasis the solar sector, the better the chances of agrivoltaics being implemented, but instead could be indicating, hand-in-hand with FiTs and governmental resources, how much space is available to expand renewable energy systems like agrivoltaics into agriculture.

Third, I find that stronger renewable energy development and agrivoltaic research encourages implementation, because it suggests that countries are looking to incorporate these systems into the agricultural and energy sectors to increase productivity. Many countries have been developing solar as part of their renewable energy systems for well over a decade, and in the past five to ten years, there has been a ‘solar boom,’ where more investment, interest, and development of solar energy has occurred. In Germany, Chile, and Thailand, they have a 59%, 70%, and 18% share of total electricity generation from renewable energy sources respectively, which each suggests different bandwidths for further development, space for solar energy, and commitment to renewable energy. Furthermore, having countries such as Germany and Chile opening agrivoltaic centers and studying their feasibility of crops such as cherries or potatoes suggest that they are planning on incorporating renewable energy such as Agrivoltaics into agricultural production. But there are also barriers that countries will face even if they have a good capacity for solar energy, such as in Thailand. Those barriers could include land mismanagement, poor regulatory processes, or little financial assistance, and until these issues are addressed with agriculture and renewable energy, implementation can be especially difficult.

Fourth, all three countries, and essentially every country in the world, has made both national and international climate-based pledges, suggesting an importance to international commitments in development. I believe that how these pledges change and are revised is a key sign of when and how a country could be ready to implement agrivoltaic systems and could be a measure of internal commitment. The biggest international climate pledge to date is the Paris Climate Agreement[16], which is a legally binding international treaty on climate change that was

[16] In 2022, the German government successfully reached its objective of providing more than EUR 6bn for climate finance (BMZ, 2023). The increase in climate finance is due to the growing demand for climate programmes in recipient countries and exceptional factors, such as special funds for food security in Ukraine, which are counted towards the goal. Initially, the government had projected around EUR 4.3 bn annually from 2021 to 2023 (Kowalzig, 2022) (Climate Action Tracker, n.d.)

adopted in 2015 by 196 Parties at the UN Climate Change Conference (COP21) in France. The general goal of the agreement is to limit global warming to 1.5°C and see an overall decline in greenhouse gas emission brought on by a number of things including climate change by 2030 (United Nations Climate Change, n.d.).

Almost every country has remained committed to this international pledge, but there are also national pledges. Chile[17], for example, continues to raise how much of their energy will come from renewables and how soon they are aiming to reach these goals nationally, when compared to the Paris Climate Agreement. This could mean they would be open to implementing new renewable systems to reach their goals, and also support the at-risk agricultural sector. As renewable energy develops and some of these countries establish a good knowledge and financial base and increase the amount of energy they create that comes from renewables, they are able to look at more co-generative and specialized systems such as agrivoltaics, to increase efficiency to continue towards these pledges and goals. Commitment to these pledges can be evidenced through actions and development, and the more that a country evidences improvement, increased investment and stronger structural factors, the better the chances of implementation are.

Fifth, I found that grid access and financial investment assistance to access the grid could be very important to implementation, especially considering that grid capacity is very poor in a lot of regions around the world and continues to get worse as it faces climate change issues such as excessive heat and increasingly destructive natural disasters. We see a lot of countries that have already raised millions to billions of dollars, and for cases like Germany and even Chile, as financial investment and improved grid accesses increase, there has already been implementation of agrivoltaic systems. Chile still faces setbacks with grid access issues. Thailand has plans to raise billions of dollars to create smart grids and support electricity generation, but has yet to do so[18]. Until financial investment in some places is raised, such is the case with Thailand, and improved grid access efforts are addressed, especially in places like Chile and the grid coordinator issues, the potential for implementation will remain limited.

[17] Chile has set national-level climate promises such as the renewable energy target of 70% renewable energy by 2030, which would beat the Paris Climate Agreement goal by around 20 years. Chilean President Piñera also created a plan that same year carbon neutrality of all economic sectors by 2050 and full phase-out of its domestic coal production by 2040 (Climate Nexus, 2019).

[18] Thailand has plans to raise $6.8 billion in investments by 2036 to create smart grids and support electricity generation (International Trade Administration, 2021).

Almost all countries in the world have some percentage of their total power generation that comes from renewable energy, and for a lot of countries, that percentage keeps growing, especially with the push from the Paris Climate Agreement and other renewable energy pledges with deadlines coming in the next decade or two. *I found that alternative power sourcing could promote agrivoltaic implementation, because countries are always looking for ways to continue to develop the share of renewable energy they produce and consume yearly, protecting themselves from climate change, and there is always room to grow and become more efficient in energy generation.* Systems like agrivoltaics promote efficiency and dual income which can be attractive for governments and farmers alike to reach several goals, such as energy independence, food and water security, and stable and diversified income, all at the same time. Lower percentages of renewable energy alternative power sourcing could indicate slower implementation because investment still needs to come in and structural changes need to take place. At the same time, as countries get closer to, for example, 70% renewable energy, there will be less room to grow, and perhaps less desire to diversify and develop other forms of renewable energy as what has been working, like hydro and wind energy, will continue to be implemented since there has already been a lot of research done on these forms of renewable energy.

Next, I found that the use of other renewable energy sources could be a contributing factor to hinder agrivoltaic implementation. Currently, many countries depend more on systems like hydropower and wind energy than on solar or other forms of renewable energy. In places such as Thailand where there is already a small share of renewable energy out of total power generation, if they have such large sections dependent on biomass and hydro power, there is little room within renewable energy to expand until more development has taken place to increase total renewable energy generation. Yet, solar energy has also been experiencing a 'solar boom' over the past decade or so, and many countries are seeing solar power become an increasingly large portion of their energy generation and use. Especially with the need for crop protection against adverse weather, as well as adverse weather affecting the efficiency of other renewable energy sources, such as hydro and the loss of water resources to drought or the lack of wind during certain seasons, implementation of agrivoltaics and other similar systems could be an option to make up for the loss of other forms of energy.

Eighth, climate change will be a big factor in how alternative power sourcing increases, because as droughts, floods, hotter temperatures, and natural disasters increase, the need to strengthen energy systems and protect water and agriculture will increase as well. Climate change is a big inhibitor to implementation of renewable energy, because of the adverse weather conditions that are changing, but at the same time creates greater opportunity to implement certain types of renewable energy that can make production more efficient and improve water conditions, food supply, and ambient temperatures. As we've already seen, increased temperatures affect solar power, wind and season changes impact wind power, and changes in perception and water scarcity affect hydro power. I believe that implementation success depends on the need-based, or the lack of need for certain solutions, like we see with Chile and how they do not necessarily have land scarcity, but they do experience land mismanagement and water scarcity and are looking to increase productivity to stay ahead of climate change crop declines. And in Thailand, the majority rainfed agricultural system is more vulnerable than the irrigated systems to the negative effects of climatic variability because it completely depends on the frequency, intensity, and timing of rainfall (Kyaw et al., 2023).

The type of crops that are produced in the country, as well as those that are compatible with agrivoltaics, are a large factor in implementation because this system is so crop dependent and regionally reliant. Based on data, vegetables such as beets, potatoes, radishes, tomatoes, peppers, and carrots, along with leafy greens like spinach and lettuce do well under agrivoltaic shading, as do berries like strawberries, blueberries, lingonberries, and raspberries. But crops such as cereals and fruit trees have not done as well, and these two categories of crops are some of the leading crops produced and exported in countries around the world (Just Energy, 2023). *Countries that are known as big cereal producers could face issues with implementing agrivoltaics into commercial agriculture, but I don't necessarily find this in my study*. Sometimes growing wheat with certain orientations of solar panels is successful with wheat, but sometimes it is not. While Chile had more potential for agrivoltaics based on crop type, Germany has developed its industry despite a heavy cereal-focused agricultural economy suggesting a predominance of other factors. There is still a lot of research to be done here, which comes from structural pathways and investment opportunities as discussed above, as well as how productive these systems will perform based on the size of farms and commercialization.

While smaller operations have been known to be better for agrivoltaic implementation, as it can help farmers adapt to climate change and diversify their income as well as increase certain crop yields and protect against increasing extreme weather (Solar Energy Technologies Office, 2023), the smaller size of these farms also means that there is decreased efficiency and lower productivity as well as increased vulnerability to crop failure, especially in one or two crop farms (Bloom Ranch of Acton, n.d.). *For starting agrivoltaic systems, it seems that smaller amounts of solar panels are also popular and have increased the most in terms of productivity and profitability on smaller and family-owned farms, which dominate many countries' agricultural sectors*. Only recently have trends towards more large and commercialized farms increased, and there are a few more barriers policy-wise to face with implementation there.

Conclusion

While a lot has been reviewed within this paper, there are still many areas that need further research to assess not only technical aspects, but how structural and governmental pathways affect the implementation of renewable energy systems such as agrivoltaics. Understanding the dependency of this system based on the factors above and considering regional differences continues to be the most important aspect of this study. When starting this thesis, I found several countries that fit the qualification for assessing success or lack thereof with renewable energy and agrivoltaic systems, and although three of them are reviewed here, countries like Greece, South Africa, Afghanistan, and Bosnia and Herzegovina also had complex implementation barriers and successes that stood out to me and could be areas for further investigation. Other areas for further research and study include social and cultural factors which can have an impact on the willingness to adapt to new systems or adopt new farming techniques, as well as past historical events such as war or financial mismanagement and bankruptcy. There could also be possible political influence within renewable energy, agricultural, and international relations, and feelings towards renewable energy over time through different political parties and indigenous groups.

Agrivoltaics, the pairing of solar panels with agriculture, has been studied extensively in terms of technical aspects like crop type, panel type and orientation, and is helpful for increased crop yield, reduced water evaporation and soil preservation, lower temperatures, diversified income and off-set prosecution costs. The purpose of the study was to analyze agrivoltaic development within specific countries of the world and identify factors related to governmental and structural aspects that affect implementation. Using the methods I have reviewed at the beginning of this paper, I was able to select Germany[19], Thailand[20], and Chile[21] as case studies which served as representatives for identifying various structural, government, and energy and agricultural based factors that have or will inhibit or encourage implementation. I have found that much research still needs to take place on this system, which is very dependant not only on financial assistance, but crop type of regionality, in order to best understand if this system is viable in different parts of the world to help address limited space and land use competition, climate change effects, a growing population, and growing demands for food and energy.

[19] See ‘Appendix A’
[20] See ‘Appendix B’
[21] See ‘Appendix C’

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Appendix A
Case Study of Germany

Germany

Positionality and Climate in Germany (Section A1)

Germany, also commonly referred to as Bavaria, is a European country with a Federal Parliamentary system and has been a highly productive member of the European Union since 1958, as one of its founding members, in order to promote economic cooperation and success across Europe. Germany was selected as one of the top, highly productive, countries for this research based on its history of successful renewable energy production and total number of agrivoltaic systems between 2015 and the present. Being a part of the EU, Germany and other European countries are participating in a goal of reaching climate-neutral status by 2025, with Germany also not relying on nuclear power or coal to make this transition (Schlick, 2024). Germany is located in a temperate region of Europe according to the Köppen climate system, meaning that their weather is less influenced by the oceans, and they experience more temperate extremes during seasons (Met Office, n.d.). These temperature regions across the world are fairly important to an agrivoltaic system, as tropical and temperate climates are often considered superior in research in terms of fairly consistent access for rainfall and sunlight, as well as its general effect on soil health. Climate behaviors impact these areas however, and changes in wind speed, solar irradiance, and extreme weather events are among some of the threats to solar PV (Soulan, 2019). Germany is experiencing some of these challenges currently with solar PV with cloudy and windless winter periods, meaning that it would need to consider investments in energy storage systems. Battery storage capability has been advancing though (ISE), and according to the German Environmental Agency, Germany has invested around €37 billion in renewable energy systems. About €400 million has been invested into German energy supplier Thüringer Energie AG (TEAG) "to upgrade and digitize the electricity grid" and €100 million has provided Deutsche Kreditbank (DKB) onshore wind and solar photovoltaic projects (Schlick, 2024).

Renewable and Solar Power in Germany (Section A2)

This country is unique because of its high standing within the economy of the European Union and its standing as one of the top economies in the world. As of 2024, Germany is the third largest economy, just outside of the United States of America and China, and just ahead of Japan, with a value of $4.92 Trillion USD. This makes Germany the largest economy in Europe, the third largest in the world, and part of this success is due to its largest service sector and reputation as the third largest exporter (Glunz, 2025). Renewable energy, especially within the past decade or so, has made considerable impacts on a country's economy. Renewable energy consumption increases in Germany by 1% could lead to a 0.2194% in economic growth, as well as increases in capital and increase in labor productivity leading to increased economic growth (Rafindadi, 2017). Outside of that fact, Germany also introduced some of its renewable energy standards very early on and has been successful in their growth and implementation, which would make it easier to introduce more Agrivoltaic systems into the grid, especially considering the work that has already been done to upgrade the electric grid and promote projects. Renewable power in Germany has been a serious economic driver, as it has added more jobs, lowered consumer costs, and could save Germany billions of dollars as it moves from imported Russian oil and gas to fully renewable energy by around 2050 (Dublino, 2024). Germany produced 504.79 TWh (terawatt-hours) of energy in 2023, which is a decrease from 644.46 TWh in 2017 (H. Ritchie et al., 2020). The country currently enjoys an alternative power sourcing of renewable energy at 57.6% of its total energy production in 2024 (Clean Wire Energy, 2024), up from 52% in 2023 largely credited to wind and solar power which makes up about 45% of the 60% total (Rangelova and Rosslowe, 2024). Currently. Germany has 6, 569 current solar projects, with around 10 more proposed and 4 under construction (Global Energy Monitor, n.d.). Germany also gains some of its 57.6% energy mix from hydropower and bioenergy: 4.3% and 8.8% respectively (Clean Wire Energy, 2025). Altogether, renewable energy generated 206 TWh between January and September of 2024 exceeds fossil fuels of 140 TWh (Rangelova and Rosslowe, 2024) and makes Germany one of the world's largest markets for renewable energy expansion and technology (Ener Data, 2025). Wind energy specifically made up around 30% or

136 TWh and is still Germany’s largest renewable energy sector (Ener Data, 2025). Solar in 2024 was around 13%, with solar having doubled between 2022 and 2023, making Germany one of Europe’s biggest producers of solar power (Schlick, 2024). While there could be some conflict within the power grid and over incentives and resources for renewable energy between wind and solar systems, wind energy will still need large increases in its production to meet German targets, while solar continues to climb at a staggering rate and contributed nearly half of the renewable energy increase in 2024 (Rangelova and Rosslowe, 2024) .Overall, the success of different kinds of renewable energy, as well as the promising record breaking progress in solar installations and generation in Germany point towards favorable conditions for Agrivoltaics. Especially in a market as flexible as the German renewables, Agrivoltaics will be able to make advancements in product quality and design, and further research the possibility of this system contributing by increasing land use efficiency and raising total solar generation.

Agriculture in Germany (Section A3)

Germany has a total land area of 357,600 km2 and a 11.7 million hectares, or around 33% (Statista Research Department, 2024), of that is the total arable land currently available for farming and crop production (World Bank, n.d.), meaning that farmers control around one-third of the cropland space. Germany is the third largest agricultural product producer in Europe, behind France and Italy, with 4% being organic farming (Climate Change Post, n.d.) and are known as top producers of important cereal grains such as wheat, barley, and rye, but also sugar beets, rapeseed, potatoes, and asparagus (Crop Trust, n.d.). However, agriculture only makes up about 0.8% of Germany’s $4.92 Trillion USD GDP (World Bank, n.d.). Aside from cloudy and windless winter periods that affect PV efficiency however, Germany also experiences vulnerabilities to its agricultural development as a result of climate change, with drier summers and extreme temperature increases that surpass crops optimum temperatures and decrease crop yields significantly. Nearly half of the farms that produce these products are small, family-run farms, which are preferable for Agrivoltaic systems because of the financial benefits to farmers, through increased income per acre in electricity generation, and land use diversification (Ballard et al., 2023) and are also generally considered more environmentally sustainable types of farms as opposed to larger commercial farms. Greening efforts have traditionally been more geared towards medium and large size farms, which puts sustainability and economic viability of smaller farms at risk (Wuepper et al., 2020). There has recently been a shift towards larger farm complexes in order to increase efficiency, but mainly in Eastern Germany, while farms remain small and family run in Western Germany (Wuepper et al., 2020). With many farms still being smaller, Germany has been experiencing recent agricultural protests related to subsidy and tax cuts and changes to fuel regulations, and furthermore with the cost of farming inputs like fertilizers and equipment, many farmers are finding it more difficult to maintain a profit. Large farms might be more equipped to handle policy changes, but both small and large German farms are at risk in a volatile international market (Kautt, 2024). Germany is a major exporter of cereal crops, but largely imports other foods, and aside from wheat which has shown increased yields in studies, cereals are not generally considered good crops for agrivoltaic systems because they require full sun. Other crops that can be grown in Germany, such as potatoes and other vegetables, have undergone studies that reveal no or insignificant affect in yield when under solar panels of varying density (Widmer et al., 2024). This is all to say that agrivoltaics can and has been implemented with crops that can be grown in Germany, which indicates that this system can be initially successful and has significant proof of stable agricultural and solar sectors to support implementation on a smaller scale. (More about land conditions and fertility – also more about how Agrivoltaics can be of help, specifically through its benefits and financial considerations, including solar as discussed above).

The Conversation Surrounding Agrivoltaics (Section A4)

The conversation surrounding agrivoltaics began worldwide in around the 1990s, yet it has really gained traction within the past several decades and especially within the last several years since the 2016 Paris Climate Agreement. Germany aims to reach net greenhouse gas neutrality by 2045. It has set interim targets of cutting emissions by at least 65 percent by 2030 and 88 percent by 2040 compared to 1990 levels. Post-2050, Germany aims for net-negative emissions (Appunn, 2025). Germany's investment in renewable energy first began in the 1970s with the introduction of wind and turbine energy credited to Aloys Wobben's Enercon business and was quickly followed in 1990 with Germany's first photovoltaic rooftop panels being introduced. At this time, conferences on renewable energy are taking place around the globe. The introduction of rooftop panels was then followed by Germany's Electricity Feed-In Act, which made it easier to introduce renewable electricity into the power grid through fixed tariffs, and served as the precursor to the 2000 Renewable Energy Sources Act [EEG]. The EEG was a groundbreaking law in Germany as it set up the legal transition into renewable energy, with higher feed-in fees for photovoltaic electricity. It went into review in 2012 for the concerns of rising costs and burdens on the industry associated with the law, before the EEG 2.0 came about in 2014 which put cost-effectiveness and reliability at the center of the green energy transition in Germany (Deutschland.de, 2014).

Looking specifically at Agrivoltaic systems in Germany, the first mention of this system does not appear until a 2021 press release, when the first Agrivoltaics research center is set up near Lake Constance in Gelsdorf, Rhineland-Palatinate with the help of the Fraunhofer Institute for Solar Energy Systems ISE. Here, they were testing eight varieties of apples with four different drop protection and solar panel systems in a five-year study (Fraunhofer ISE, 2021). Data surrounding the overall development of agrivoltaics is hard to come by, outside of individual project reports or general research. While Agrivoltaics was in conversation around the 2010s, interest has grown considerably since 2020. By 2020, seven agrivoltaic facilities had been constructed. Germany has built 21 agrivoltaic facilities as of March 2023, many of them research facilities, with a combined capability of around 81 MWh (megawatt-hours). This capability is expected to rise upwards of 400 MWhs between 2023 and 2024, in large part due to the changing legal environment surrounding renewables in Germany. It is also estimated that at the end of 2024, there were some 45 agrivoltaic facilities operating in Germany (Pump et al., 2024). Sometime in 2026, Germany is expected to finish construction of what would be Europe's largest agrivoltaic facility called Klimapark Steinhöfel project in Brandenburg, spanning 500 hectares and generating around 750 MWh of electricity (SPIE, 2024). Along with the fast-paced development of agrivoltaics in the past five years, The German Energy Agency (DENA) has identified agrivoltaics as a key technology for achieving energy and agricultural production goals and plans to expand capacity for agrivoltaics to one GW (gigawatt) by late 2025 (Adkins, 2023). Furthermore, in 2024, a survey released by the Fraunhofer ISE showed that around 73% of German farmers are considering integrating an agrivoltaic system onto their land, mainly due the income that it would generate as well as the usefulness of the technology (Bellini, 2024.)

The results from R Studio, mentioned above in methods, have been especially helpful in discerning regions and countries where there is high agricultural activity and also supposed solar farms or energy production. Germany, along with six other countries around the world, were the only ones to show data of the highest agriculture production along with the solar data fed into R Studio. Germany had nearly double the amount of threes as any other country, with 5 3s, followed by 1,137 2s, which also equaled relatively high agriculture production. The question then becomes where these systems are located, and for Germany, some smaller scale agrivoltaic projects can be found in roof-mounted forms, on barns and greenhouses with semi-transparent panels for specialty crops (Song et al., 2023). But many of the current agrivoltaic projects are research facilities and field-mounted systems that are raised to particular heights to allow growing wheat and potatoes (Fraunhofer ISE, 2022) and mechanical farming activities (Enkhardt, 2022). As discussed above, while there have been high agricultural production rates, many of the farms, especially in the west are smaller family-owned farms can benefit from the research being done at German agrivoltaic facilities to be able to increase their income in times over underlying financial strain, and also optimize their land use efficiency.

Agrivoltaics have advanced many ways in such a short period of time, within a country that is known for its dominance in both solar and agricultural sectors and suggests that it could continue to grow in popularity within the country and be another potential renewable energy system that supports climate related goals and solves issues of land use and energy generation.

Appendix B

Case Study of Thailand

Thailand

Positionality and Climate in Thailand (Section B1)

Thailand is a southeast Asian country known for its tropical climate, food adventures, and friendly citizens. It sits right near the equator, bordered by other tropical paradises such as Vietnam, Cambodia, and Malaysia. Thailand is the founding member of ASEAN or Association of Southeast Asian Nations, has the second largest economy in Southeast Asia, and ranked 23rd in world economy making it a newly classified industrialized economy that focuses on agriculture and manufacturing (Wikipedia, 2025). Although Thailand has been a parliamentary constitutional monarchy since 2019, due to its history with oscillating between military and democracy rule, it continues to have its politics influenced by the military (Hafner et al., 2025). Its role in Asian governments and its historical record, as well as its high productivity in agricultural and solar activity which rivals Germany, as well as developmental proof of supportive renewable energy policy, is why it is a selected country for this study. Furthermore,

Thailand is classified as a tropical climate, meaning that the area experiences higher temperature and higher levels of rainfall, as well as increased biodiversity and a carbon-rich environment, which are becoming increasingly ideal for agrivoltaic success as agriculture migrates to the global south and more tropical climates (Coelho et al., 2023). With this diverse and weather dependent climate, Thailand is beginning to experience effects of climate change, which is influential to its agricultural sector that makes up a large portion of the country's GDP. The majority of issues associated with climate change, such as drought, unpredictable rainfall, and diseases have been attributed to human activity, and farmers are concerned that this could lead to changes in "growing seasons, species composition, water needs, and soil properties, and increasing risks of pests and diseases" which could in turn bring food insecurity, economic instability, and disruption of many people's livelihoods and income, across much of Southeast Asia specifically and Thailand, who is known as the "Rice Bowl of Asia" (Coelho et al., 2023). Currently, the Thai are coming up with ways to combat climate change effects which threaten agriculture and general state advancement, such as water management, institutional support, and community engagement. Farmers are also preparing for changes by adopting alternative farming techniques, crop diversification, and water management strategies, which is where agrivoltaics could be one sustainable solution that provides increased crop yields and improved water retention, while diversifying and bolstering income and economy (Coelho et al., 2023).

Agriculture in Thailand (Section B2)

Thailand is an Indochina peninsula known as one of the most agricultural countries in the world, having about 513,120 km2 (Hafner et al., 2025) or 51 million hectares of nutrient-rich total land space (Coelho et al., 2023). About 41% or 21 million hectares of that is dedicated to some form of farm holding or crop production, with 17% of that being irrigated land (Chainuvati & Athipanan, 2001). As much as 78% of that land is heavily dependent on rainfed farming, meaning that it is heavily dependent on weather (Coelho et al., 2023). From 2015 to 2022, Thailand experienced a small dip followed by a larger rise in total arable land in the country, going from 33.1% in 2015, to 32.7% in 2018, and then to 33.5% in 2022 (Trading Economics, 2022). This has been attributed in large part due to land degradation over time due to deforestation and improper land management, which costs Thailand $2.7 billion USD or 1% of country GDP, as well as heavy monsoon rains followed by increased seasonal droughts that degrade the quality of soil (Wijitkosum, 2020). Between 2015-2016, Thailand experienced one of its worst periods of drought with critically low water levels in reservoirs, which affected mainly central and northeastern areas (Kyaw, 2023). In Thailand, like in most other southeast Asian countries, rice is the main crop produced, along with wheat, maize, cassava, and rubber, as well as fruits such as mangoes and tangerines. Their tropical climate makes this area very ideal for growing cereals and tropical fruits, both of which are highly commercially produced and bolster the economy (Kyaw, 2023). Nearly 7.7 million single-crop growing farm families are actively engaged in agricultural activity in the country, which is up from around 6 million in 2015 (Walderich, 2025) and while it has seen some decline in recent years, which could be reasonably attributed to climate related decreases in land, there are some 13 million workers in the agricultural sector. This makes up 30% of Thailand's total workforce, with legal and illegal migrant workers from Cambodia, the Lao People's Democratic Republic, and Myanmar being used to fill labor shortages (International Labour Organization, 2022).

Thailand is notably one of the world's top rice exporters in the world, second to India, moving 7.5 million metric tons of rice in the 2024/2025 period (Shahbandeh, 2025). With all of this, it is clear why 8.6% of Thailand's GDP is composed of agricultural activity (World Bank, 2023) and involves around $545 billion USD (International Monetary Fund, 2024), compared with Germany whose agriculture GDP is 0.8% and Chile whose agriculture GDP is 3.5% (World Bank, 2023). Unlike in Germany, where cereals are the main crop product and not a popular agrivoltaic crop because of its high shade intolerance, rice has proven to be a financially successful crop grown with solar panels even if its overall yield decreased due to shade intolerance. Rice has also seen data where the rice yield could initially increase but eventually will decrease over the later part of this century by around 8.4%, in a study looking between the years 2020 and 2099, or that rice yields could decline more noticeably due to adverse effects associated with increased temperatures, including water stress (Coelho et al., 2023). Others claim that higher temperatures had no significant impact on rice yields, but did on maize yields (Kyaw, 2023). These are multiple studies that can only be done by looking at potential scenarios and where results can vary significantly, but the future is so uncertain that this is one of the only options when looking at consumer crops. There is limited work that has been done on main consumer plants including rice and cereals, especially when compared with shade tolerant plants and leafy greens, which are very successful and high-yield under PV panels and are considered the most ideal for agrivoltaics. Furthermore, with Thailand experiencing both high levels of drought and unpredictable and heavy rain seasons, both of which disrupt crop growth, Agrivoltaics could be a solution. Agrivoltaic systems are known to create advantages for crop production by protecting crops from adverse weather effects such as heavy rain, and can also aid water retention in soil and decrease evaporation due to shade over the soil. With Asian countries like Thailand beginning to search for and implement adaptive agriculture features such as risk management and water management, and general stakeholder engagement and knowledge management according to the United Nations Framework Convention on Climate Change [UNFCCC], renewable energy and dual-land-use systems to increase productivity and income through diversification such as Agrivoltaics can be considered to aid (Coelho et al., 2023).

Renewable and Solar Energy in Thailand (Section B3)

Thailand aspires to actively transition to over 30% renewable energy by 2037, using a variety of sources including wind, solar, biomass, biogas, and hydropower, by building more renewable energy power plants over a 20 year period. According to the International Renewable Energy Agency (IREA) and the Ministry of Energy, this switch to renewables could save the country upwards of $9 billion USD. Thailand is currently looking to create smart grids to support electricity generation, and this includes calling on $6.8 billion in investments before 2036 in order to “enhance energy supplies, increase efficiency, strengthen grid resilience, and reduce carbon emission.” Renewable energy in Thailand has more than doubled since 2012, which is attributed in large part to hydropower and bioenergy, with solar and wind power also quickly catching up (International Trade Administration, 2021). In Thailand, renewables make up a total 18.3% of their total energy generation (International Energy Agency, 2022), which was at 223.3 TWh capacity in 2023 (Walderich, 2024). While biomass energy takes up the largest share of renewable energy in Thailand at 28.8%, solar energy is followed closely behind with 25.2% of total renewable energy (International Trade Administration, 2021). According to the global energy monitor, Thailand has around 430 solar projects that are active, along with 6 new announced projects and 1 project in construction (Global Energy Monitor, n.d.). And, out of the 190.49 TWh of total electricity generation in Thailand, 5.24 TWh or 1.20% of that is solar energy production (International Energy Agency, 2022). Hydropower and wind also make up a considerable amount of energy produced, and out of all renewable energy used in Thailand, most came from solar, biomass, and hydropower (International Trade Administration, 2021).

Thailand is considered a newly industrialized country, due in part to its low unemployment, low poverty levels, and increasing tourism rates. Employment rates sat at around 1% in 2022 with a large part of the population working either in subsistence agriculture or in other employment like family work. Thailand is the second largest economy in Southeast Asia, behind Indonesia, and the ninth largest economy in all of Europe. The industrial and service sectors are its biggest sectors of the economy but also have an agricultural sector that produces 8.4% of the GDP, behind trade and communication sectors (Wikipedia, 2025). Together with the nation's development, renewable energy consumption and production increases by just 1% could bring a 0.57% increase to Thailand's economy (Fazal et al., 2020). A transition to a renewable energy system at the rate that Thailand is moving, along with its boost in a growing economy, could mean over 1 million new jobs, as well as better energy security, improved environmental health, and a decrease in health concerns attributed to fossil fuel energy, such as cancer and heart disease (Energy Research Institute et al., 2022). Furthermore, continued progress towards goals of renewables could save $19 billion in energy imports annually and encourage around $15 billion in private investment (Climate and Development Knowledge Network, n.d.). According to all of this, Thailand has a promising solar sector that continues to see year-to-year growth rates as well as supportive policies like smart grids, investment, and feed-in-tariffs. For the nearly half of the population that works or is somehow involved in farming in Thailand, utilizing Agrivoltaics and solar energy to diversify not only their land use but also their income streams and benefit from the supportive push towards more renewable energy in the country could be a good route to take.

The Conversation Surrounding Agrivoltaics (Section B4)

Thailand has had a strong and storied investment in renewable energy, beginning in 1983 when EGAT, the Electricity Generating Authority of Thailand, began using the Phrom Thep Renewable Energy Station to carry out research on electricity generation from wind power. In 1989, the first Geothermal power plant was constructed in Thailand with the help of EGAT.

EGAT is in charge of generating electricity from main fuel sources such as fossil fuels but also carries out research and development on types of renewable energy. And, in 1986, the first hybrid solar cell station was produced. (Biomass energy brief overview and any competing energy sources to solar). Solar energy has been continuously studied and developed in Thailand within several provinces in the form of large solar farms, and involves solar cell demonstration stations, solar cell plants, and even hydro-floating solar systems (Electricity Generating Authority of Thailand, 2021). In 1993, Thailand implemented its first solar off-grid program in order to electrify rural villages, schools, and water pumps, which was fully funded by the government with regular maintenance occurring to produce around 30 MWp [megawatt-peak]. This was followed several years later, in 2007, by a feed-in policy called the Adder premium policy which provided financial incentives for small and very small power producers to help them to invest in renewable energy, with the goal of stimulating private sector participation in renewable energy generation (Solar Magazine n.d.). The Renewable and Alternative Energy Development Plan [AEDP] came in 2012 as a decade-long project to increase renewable energy by 25% by development of solar, wind, hydro, and biomass energy, and marked a shift from the Adder plan to this one. This was revised in 2015 as the Alternative Energy Development Plan 2015-2036, which aims for renewable energy to comprise 30% of Thailand's total energy consumption by 2036. Then in 2018, the Power Development Plan [PDP] was produced by the Thai government in order to support renewable energy advancement. This plan also sets up clear objects for the country in achieving renewable energy advancement (Lertvittayachaikul et al., 2024). This development has made Thailand a regional influence in renewable energy as they continue to produce renewable projects centered around biomass, solar, and wind.

The conversation surrounding Agrivoltaics specifically has a much more recent start, beginning in the 2020s as worldwide interest in renewable energy and international commitments increased. There is not much specific evidence surrounding when the first agrivoltaic farm began or even how many agrivoltaic farms exist in the country, due to a variety of factors including a general knowledge gap and a lack of knowledge about this system, especially for those involved in agriculture in Thailand. While Thailand doesn't specifically face land scarcity, it does suffer from inefficient land use, which Agrivoltaic systems could aid with by combining both solar and agriculture and also diversifying long-term income for farmers (School of Renewable Energy and Smart Grid Technology & Naresuan University, n.d.). Despite all that we know about the technical side of agrivoltaics, and the ways in which Thailand is a prime candidate for implementation of these systems due to its high agriculture and growing renewable energy sectors, agrivoltaics has yet to be implemented here. But, there are encouraging signs, such as a Thailand Agrivoltaics Policy Recommendations Validation Forum that took place in Bangkok under the Clean, Affordable, and Secure Energy for Southeast Asia project for Southeast Asia. Here, policies such as defining land use categories specifically for agrivoltaics and implementing incentives and subsidies for financial support to farmers for implementation (Thitikorn, 2024).

As mentioned above with Germany, there were a handful of countries that had a ranking of 3 on the R studio results, indicating high agricultural production. Thailand had 3 3s in this result set, along with 104 2s, which also equaled relatively high agriculture production. While not nearly as many as Germany, both in terms of 3s and 2s results, the amount of high agricultural production and suggested high solar output in those regions suggests that Thailand is a prime candidate for adopting some sort of renewable energy system such as agrivoltaics. The question then becomes where these systems are located, and for Thailand, as discussed above, many of the suspected agrivoltaic and just general agricultural land is located from family farms to commercial estates. However, more often than not, farms in Thailand operate on a small scale in the form of family owned and operated farms which are generally passed down through generations of farmers. The small farm clusters in nearly 50% of farming households and being one or two crop farms is attributed to lower productivity levels (United Nations Thailand, 2020). Research also suggests that much of Thailand's solar systems are located in central and northeastern regions of the country due to higher solar radiance (Trade Commission of Spain in Bangkok, 2022), in larger utility-level facilities, which are ground mounted PV systems and account for nearly all solar systems in Thailand due to a ‘solar adder’ fiscal policy (Solar Magazine, n.d.). Rooftop solar systems are also becoming more popular in a commercial and industrial sense, as are float solar hybrid farms (Tycorun, 2024).

As evidenced above, Thailand has abundant sunlight and extensive agricultural land which offers significant potential for the adoption of agrivoltaic systems, especially in the northeast and central regions of the country. Investment and collaboration with public and private enterprises in the country will be critical to spreading development and knowledge about these systems, as well as encouraging agrivoltaic implementation.

Appendix C

Case Study of Chile

Chile

Positionality and Climate in Chile (Section C1)

Chile is a country which extends across the majority of western South America, sharing a coast with the Pacific ocean and the Andes mountain range making up much of the country's geography. It is otherwise known as the Republic of Chile, this country has a long history of representative democracy with a few exceptions such as military coups and a brief period under an authoritarian dictatorship (Johnson et al., 2025). Chile is a member of several regional and global alliances, including the Pacific Alliance and Community of Latin American and Caribbean States, as well as the United Nations. They currently hold a seat on the UN Human Rights Council for the 2023-2025 term and is also a member of the Americas Partnership for Economic Prosperity. Chile was selected as a country for this study because of investment and development in renewable energy as well as climate change precautions, especially when compared to other South American countries. In 2019, Chile served as the president for the United Nations climate change conference and has been committed to a sustainable future (Bureau of Western Hemisphere Affairs, 2024). Chile is also an interesting candidate for agrivoltaics and general renewable energy systems because of its vast range of climate zones and geographical features, including the Andes mountain range.

Interestingly, Chile is an area that experiences several extreme natural disasters, such as volcanic eruptions, earthquakes, and tsunamis. Because of the length of the country, 2,700 miles, spanning from Peru to the tip of the South African continent, it experiences climate zones ranging from tropical rainforest and coastal desert at the northern tip to a cold subantarctic southern tip, with temperate regions in the middle and a landscape dominated by mountain ranges and coastal depressions. There are also many rivers that cross the country, and valleys of agriculture that line them. With climate change altering the temperature of the world and behavior of weather, Chile is expecting to see changes in the frequency and severity of natural disasters including wildfires, floods, and droughts (Wikipedia, 2025). These types of changes can have a big impact on manufacturing and agricultural activities that take place in the country and have implications for economic growth and development in regions of Chile for electricity generation, agriculture, and public health (Climate Change Knowledge Portal, n.d.). At this time, Chile has developed a disaster risk management plan and a climate risk atlas and is currently looking at improving and developing its energy sector but continuing to invest in renewable energy and diversifying its energy sources to combat climate change effects (International Energy Agency, 2024).

Renewable and Solar Energy in Chile (Section C2)

Chile has been developed as a newly industrialized country and leader in renewable energy technology and information awareness, as it sets the goal of having 70% of all its energy come from renewable sources by 2030 and become carbon-neutral by 2050. The transition into a global and regional renewable energy leader has come from a combination of political support and green technology. According to a study from Yale, nearly 91% of Chileans believe that climate change should be a government priority, and in recent years the center-right government published an energy transition plan that includes its climate goals and accelerating wind, solar, and geothermal energy across the country (Conley, 2023). Although wind, solar, hydropower, and biomass energy accounted for only 6% of the country's energy production in 2014, that figure has grown to 25% since around 2021, marking a nearly 20% increase in the span of seven years (Schroeer, 2021). Currently, renewable energy sources made 70% of their energy generation in 2024 with 30% being from fossil fuels (Broadbent, 2025), which is up from 51% in 2022 (Statista Research Department, 2024). Hydropower makes up 45% of the renewable energy in Chile, with wind and solar closely behind. However, hydropower continues to be at risk because of projected decline in precipitation and streamflow due to climate change, leading many to believe that other energy sources such as wind, solar, and geothermal could combat the loss of hydropower capacity. Solar makes up 34.6% of Chilean renewable energy, wind accounts for 18.4% and geothermal at 0.9% with a minimal amount of solar thermal energy accounted for as well (International Energy Agency, 2024).

Many sources, including the NRDC, predicted in 2013 that with Chile's fast switch to renewable energy over the past decade or so, from 2013 to 2028, they could add more than $2 billion USD to the GDP and create a more stable supply chain, with realistic assumptions that it could produce net benefits of $251 million USD and save $2 billion USD in fuel costs as well (NRDC, 2013). Chile is considered a high-income country and is ranked the fifth strongest economy, third place behind Uruguay and Panama in terms of GDP per capita in Latin America (Sanchez, 2024). In 2023, Chile was ranked 46 out of 195 countries in terms of economy (Observatory of Economic Complexity, 2025) and currently has a GDP size in 2025 of $343.82 billion USD (International Monetary Fund, 2025). As of 2024, Chile saw a 231% increase year-on-year of renewable energy investment, which totaled to about $5.7 billion USD which has been used to fuel growth in solar and wind projects (Jacobo, 2025). And right now, with all other incentives to develop solar energy, the country aims to provide a stable and low-cost supply of electricity and has since set a record average price of less than 2.4 US cents per kilowatt-hour for electricity from solar and wind power facilities in 2021 (Schroeer, 2021).

Since 2015, solar capacity has grown from 1,261 GWh to 17,748 GWh in 2023 (International Energy Agency, 2024) and together with wind made up 33% of the 70% renewable energy throughout 2024. Currently, solar accounts for 21% of that energy mix, which increased from just 8% in 2019 (Broadbent, 2025). Due to the low cost of solar and the favorable natural conditions of Chile, solar power alone has been predicted to make up to 46% of total energy generation 2060, primarily taking place in northern sections of the country that experience more solar radiation and temperate or tropical weather (Zlatkova, 2024). According to the Global Energy Monitors' global solar power tracker, Chile has 257 current solar projects operating, as well as 17 in construction, 109 in pre-construction, and 2 more announced projects, which can be found in central and north Chile (Global Energy Monitor, 2025) where some of the highest solar radiation is recorded in the world (Johnson, 2025). Out of its total energy generation of 83.61 TWh (Richie et al., 2020), Chile produced 17.75 TWh or 20.2% of solar energy (International

Energy Agency, 2023). Being that Chile is looking to continually expand its renewable energy sources and specifically promote investment in solar energy while also trying to find ways to combat climate change effects like drought, Agrivoltaics could be one solution that has been proven to diversify and increase solar energy while also protecting against water evaporation and promoting crop production.

Agriculture in Chile (Section C3)

Chile, as discussed above, is a very long and narrow country in South America, with a length of 2,700 miles, but a width of only on average 110 miles, maximum of 217 miles, and a minimum of 9.6 miles (Johnson et al., 2024). Chile experiences around 18 major climate types according to the Köppen system, with only a select few valleys and coastal depression hosting good agricultural land and the rest being dominated by the Andes mountain range (Wikipedia, 2025). Chile has a total land area of 756,101 km2 or 75,610,196 hectares, with 1,313,900 hectares or nearly 2% of that being arable land (World Bank Group, 2023). On this arable land, while Chile produces cultivated crops such as wheat, corn, and oats, they are most known for their fruit production and exports. Exports from fresh fruit in Chile generated almost $4.4 billion in revenue and makes them the third largest fruit producer behind China and India. Chile is the world's leading exporter of fresh cherries, prunes, and dried apples and is the second-largest exporter of fresh plums, shelled walnuts, shelled hazelnuts, raspberries, blackberries, and frozen blackberries (Malheiros, 2023). The country is also involved in 33 international trade agreements which covers around 65 markets worldwide (International Trade Administration, 2023). Out of its GDP size in 2025 of $343.82 billion USD (International Monetary Fund, 2025), Chile devotes around 3-4% of its GDP to agricultural activity year-to-year between 2015 and 2023 (World Bank Group, 2023). Most farms in Chile are small-scale farms that have small production values that require energy efficient equipment to reduce production costs and remain competitive (International Trade Administration, 2023), however there are also some larger scale commercial farms that employ hundreds to thousands of workers (Cooke, 2022). Although many farms in

Chile are small-scale operations, with a population of over 19 million (World Health Organization, 2022) the Chilean agriculture sector employs 6.32% of the country's workforce. This is actually a decrease from 2015, where the employment rate in agriculture was around 9.18%. The largest sectors for employment in Chile are industry and services, with 22.81% and 70.88% respectively (O'Neill, 2025).

Many of these fruit products are being cultivated in the central valley of Chile, where temperate and sometimes tropical temperature conditions are common, and seasons are predictable (Johnson, 2025). While leaf greens and root vegetables are the most reliable crops when paired in an agrivoltaic system, some low-lying fruit plants as well as general fruit orchards have had successful production when shading is taken into consideration, although there has been very little research done on fruit crops and agrivoltaics in general. Some recommend that instead of using temporary plastic shading to protect plants from climate-related weather conditions, they could be replaced by PV panel anchors but recommend a shading threshold of 30% as to not reduce yield while also promoting water retention (Magarelli et al., 2024). For fruit, they face climate-induced issues such as fruit splitting, flower loss, and plant diseases, which result in inferior product quality and production loss. While climate change continues to affect agriculture production and the amount of arable land available, Chile is fostering sustainable agriculture and energy related policies such as investment and funding mechanisms, and plans to combat water scarcity (WIPO Green, 2023). Systems such as Agrivoltaics could be essential to this combined plan of improving agricultural production, while also growing energy, and has been mentioned in a few articles such as the WIPO Green article. Agrivoltaics is known to improve water retention as well as overall crop yields, which will be needed in more arid parts of the country. Agrivoltaics can also help with income diversification.

Conversation Surrounding Agrivoltaics (Section C4)

The conversation surrounding renewable energy in Chile became significant around 2008, when Chile introduced a law that set a target for renewable energy of 10% by 2025, and also defined non-conventional renewable energy (NCRE) like geothermal, biomass, wind, and solar power. This was all first triggered by a gas crisis that the country faced and wanted to reduce their reliance on countries like Argentina for gas imports and high electricity prices. By 2013, another law was introduced that moved the renewable energy goal up to 20% by 2025 and streamlined several concession processes and while progress had been slow in the beginning, this accelerated the transition to renewable energy so that the country would not be vulnerable again to energy imports (Wikipedia, 2024). This advancement was closely followed by the 2014 inauguration of the Amanecer Solar CAP, a photovoltaic power plant with the capacity to produce 270 gigawatt-hours per year and making it one of the largest in Latin America. The years of 2014 and 2015 saw several other solar plants go online as well, and as of 2023 solar energy provided 19.9% of national electricity generation in Chile, compared to less than 0.1% in 2013 (Wikipedia, 2025). Since 2016, the demand for electricity, which rose 11% between 2016 and 2021 in Chile, has been met almost exclusively by wind and solar energy production while emissions have dropped 6% in that same period (Fulghum & Bruce-Lockhart, 2022). Within that same time period, Chilean President Piñera set another new renewable energy target of 70% renewable energy by 2030, which would beat the Paris Climate Agreement goal by around 20 years. President Piñera also created a plan that same year carbon neutrality of all economic sectors by 2050 and full phase-out of its domestic coal production by 2040 (Climate Nexus, 2019). And as of 2024, Chile has accounted for almost 61% of its energy as renewable energy while also aiming to achieve 80% renewables by 2030 (Climate Action Tracker, 2024). However, Chile's story of renewable energy development does not end there, as it continues to invest in new ways of producing clean energy and making the country more efficient.

Agrivoltaics began its development in Chile due to the vulnerability of its agricultural sector and the risk of high-quality soil degrading due to erosion, contamination, and improper agricultural practices. Furthermore, climate change puts Chile at risk with higher average temperatures and lower rainfall levels which will affect the water availability and production in central and northern areas. This system has been suggested and introduced in Chile with the goal of maximizing land use efficiency while also reducing water evaporation and protecting crops from harsh weather, especially in arid/semi-arid zones. Agrivoltaics began in 2017 with the introduction of three pilot plants near Santiago de Chile, the capital of Chile and located in the Central Valley area. Each of these pilot plants have a 12.48 kWp capacity and were placed in vegetable fields of a farm with fix-mounted PV panels (Gese et al., 2019). At these various locations around Santiago de Chile, researchers were testing which plants worked with shading from the panels and also measured things such as solar radiation, temperature, and humidity. One of these plants was placed in an area with connection to the electricity grid but with frequent disruptions, and it was able to provide power to seven families (Halney, 2018). Then in 2023, a 20 hectare, 9MWh distributed-scale agrivoltaic farm, Ayla Solar, began operating and working with a variety of different cherry tree species to determine its shade tolerance within twin row PV tracker panels (Wikipedia, 2025). Many of these current projects are being developed on a larger scale than in other countries. While agrivoltaics is becoming more popular in Chile with farmers, it has yet to be fully commercialized due to its high initial investment costs and poor regulation for project development (Schönberger & Jung, 2022).

Despite not having any 3s within the R Studio results in this study, it is clear from above why Chile could be a potential site of agrivoltaic growth and implementation and has in fact already started the implementation process. However, there are also some interesting results from both R Studio and the Global Energy Monitor that suggest structural and climatic factors are at play to hinder agrivoltaic and general renewable energy implementation. Chile, with RStudio results, displays 4 2s, which means there is good agricultural production, even if it isn't considered the highest. These results are looped in with hundreds of thousands of other 2s from countries all over the world, suggesting that it is one of dozens of countries that experiences average agricultural production, and also is sited near solar farms or solar activity. On the other hand, what is the most interesting result from this study of Chile is the number of cancelled solar projects. As stated above as well, Chile has 257 operating solar farms and plants, as well as dozens more in construction or being announced. Chile has 8 shelved projects as well as 23 cancelled projects. This is significantly more than Germany, which had zero cancelled projects, and Thailand, which had three. It's not to say that this is an astronomical number, considering that Greece had around ninety cancelled projects, the United Kingdom had 76, and the United States had 338 (Global 4Energy Monitor, 2025). Those results can be attributed to past historical issues such as war or financial troubles, or even political unrest. The results in Chile could suggest that there have been barriers to implementation of renewable energy systems that have yet to be fully studied.

In order to understand how successful implementation of agrivoltaic systems takes place around the world, we must look past what is already known about these systems and the technical research that has been done on them. However, the government and structural pathways to implementation also need to be researched and understood, and that is the purpose of this study.

Appendix D

Identified Drivers and Barriers to Agrivoltaic Implementation Internationally

	Germany	Thailand	Chile
Feed-in-Tariffs (FiTs) and Other Government Support Systems			
Results	Had the Electricity Feed-in Act before creating the 2000 Renewable Energy Sources Act and revising it in 2015 to create reliable and cost-effective legal avenues for transition to renewable energy.	Created the 2007 Adder Premium Policy to provide financial support to small and medium producers and stimulate the private sector into participation, and has also provided fixed prices for renewable energy, low interest loans, and tax exemptions.	Introduced the 2016 Transmission Law to enhance the state's role in energy planning through open grid access and interconnectivity, has tax credits such as 27% to 25% and a 2% tax that can be deducted through equipment investment and a $110 million loan program through the European Investment Bank.
Implications	Germany has continued to be committed to renewable energy and is willing to adapt to the needs of the industry and its citizens in order to make it accessible while tackling climate change effects, making agivoltaics a strong possibility.	Thailand has interest in promoting renewables, especially for smaller and medium operations which would make it easier to implement research based agrivoltaic facilities for the family-owned farms that dominate agriculture, especially in terms of financial accessibility and income generation.	Chile has created several avenues for investment in renewables and has made the grid easier to access, meaning that connecting agrivoltaics to the grid would be easier and financially supported.
Size of Economy and Agricultural Sector			
Results	Germany has the largest economy in Europe and the third largest in the world, with a $4.92 trillion USD GDP, but they only contribute 0.8% of that GDP to agriculture while the service sector takes up the largest portion.	Thailand has the second largest economy in Southeast Asia at $545 billion USD GDP and its agricultural sector makes up a staggering 8.6% of the total GDP, being the largest rice exporter in the world.	Chile has a GDP size of only $343.82 billion USD as of 2025, but devotes between 3-5% of that GDP annually to its agricultural sector as one of the world's top producers of fruit.
Implications	Germany has the highest access to technology and financial support to implementation of renewables, but there might not be a higher demand or interest for agrivoltaics within agricultural communities because of the small amount currently invested in that sector.	Thailand, while having a smaller GDP than Germany, has plenty more room to expand their renewable energy not only within the country, but specifically within the larger agricultural sector and agrivoltaics, where there is plenty of financial support and potential interest in increased production and efficiency through co-generative methods.	Although a much smaller economy of scale, there is still a large portion of GDP dedicated to the agricultural sector to stimulate fruit and crop production and as another country with a higher interest and capacity for agriculture, implementation could be a welcomed addition to raise income and productivity.
Renewable Energy Development			
Results	Germany first mentioned agrivoltaics in 2021 by building its first agrivoltaic research facility near Lake Constance in partnership with the Fraunhofer Institute for Solar Energy Systems ISE, before going on to build 21 other	While facing issues with projects not yet being fully commercialized due to high investment cost and poor regulations, Chile has built four agrivoltaic plants within the Central Valley (three near Santiago) to test panel shading with plant	Thailand has been promoting renewable energy since 2012 and has several operating solar plants, but still does not have any operating agrivoltaic facilities or plants, and has not made any indications of implementing these

	facilities due to a changing legal system and estimating around 45 facilities completed by the end of 2024.	type such as varieties of cherry trees at Alya Solar, and solar radiation and temperature in relation to plant yield, as well as test the grid connection.	systems, whether due to a knowledge gap or no need for the system.
Implications	Germany has displayed a clear desire to keep building research facilities, indicating success in energy generation and crop yield, and suggesting that they are planning to incorporate agrivoltaics into their renewable energy production and agricultural sector	Chile will face barriers to expanding agrivoltaic implementation until regulatory processes and financial assistance can be provided, but have also suggests that they are trying to incorporate these systems into the agricultural sector to increase productivity as a major fruit producer.	Thailand faces serious barriers to implementation which is evidenced by their lack of agrivoltaic farms despite having a robust renewable energy commitment and a large agricultural sector, yet suffers from land mismanagement and could benefit from the co-generation that agrivoltaics provides.
International and National Climate-Based Pledges			
Results	Germany, while being a major contributor to the Paris Climate Agreement, has created the Climate Action Plan 2050 which aims to reach net greenhouse gas neutrality by 2045, as well as another pledge to cut emissions by around 65% in 203 and 88% in 2040.	Thailand has created two major plans or pledges, including the Alternative Energy Development Plan in 2012 to develop solar, wind, hydro, and biomass by 25% then revised in 2015 to make renewable energy compromise 30% of Thailand's total consumption by 2036, as well as the Power Development plan to support renewable energy advancement and set clear objectives for that advancement.	Chile has an extensive history of revising and pushing for renewable energy development and production, and since 2008 when they set a target for 1-% renewable energy by 2025, they have set a new goal of 70% renewable energy by 2030, beating the Paris Climate Agreement by 20 years.
Implications	Germany is looking to accelerate its climate change adjustments beyond what is internationally agreed as feasible, suggesting not only based on technology and progress made in renewables that it plans to beat the international agreement, but that it is capable of implementing systems quickly and could be open to looking for new systems to develop/implement as it tries to reach these goals.	While Thailand has not implemented Agrivoltaics, based on the revisions of its goals it is expecting to keep developing renewable energy at a fast pace and looking to grow the renewables sector, which could mean that it is looking for new ways to supplement renewable energy production, and has plans in place to implement things such as agrivoltaics.	Chile is dedicated to developing renewable energy and could be open to implementing and developing more agrivoltaic systems to support its towering goal of 70% renewables while also benefiting its successful agricultural sector.
Climate Change Effects			
Results	Germany experiences temperate region weather that is less influenced by the oceans but experiences more extremes during seasons, yet they began to experience loudy and windless winter periods, which affect solar and wind energy generation and are forcing them to consider investment in energy storage systems.	Thailand is in a tropical climate zone and typically experiences higher temperatures and higher levels of rainfall, yet has been experiencing increasingly unpredictable rainfall and longer periods of drought and disease which could lead to food and water insecurity, economic instability, and livelihood disruption.	Chile experiences climate zones from tropical to polar and as a result extreme natural disasters such as volcanic eruptions, earthquakes, and tsunamis, and through climate change these are expected to increase in frequency and severity along with wildfires, droughts, and floods which impacts manufacturing and agricultural activities.
Implications	Because of the decrease in solar radiation as well as the effect that this	Given that tropical climates are already popular for both solar energy	There is a lot of room for different effects to both solar energy and

	weather might have on agriculture, it could prove to be beneficial given the need for other forms of renewable energy and more solar panels in summer to supplement lost power, as well as protection for crops.	development and agricultural success, especially in the global south, agrivoltaics could be an option in Thailand to help with water scarcity and retention, with farms being rainfed rather than irrigated, and protect crops from adverse weather and boosting crop production given that they are already vulnerable to droughts, disease, and higher radiation levels.	agriculture within the various climate zones in Chile, and with the increase in natural disasters and unfavorable weather conditions, the need for protection from crops and retention to help with water scarcity and therefore food scarcity could pose as encouragement to implement agrivoltaics.
Crop Types			
Results	Germany is a major producer and exporter of cereal crops, which are not highly compatible with agrivoltaics, but also can grow other crops in the country such as potatoes and vegetables which are not as affected by panel shading or stand to increase productivity because of it.	Thailand produces rice as it main crop, along with wheat, maize, rubber, and fruits like tangerines and mangoes, and rice has proven to have mixed but somewhat unaffected yields, meaning that it will need further study, and is also a very financially productive crop due to income prices from solar generation.	Chile produces wheat and corn but is a massive producer and exporter of fruit such as cherries, prunes, apples, plums and various varieties of berries, which is good news as fruits such as apples, cherries, and berries can adapt to shading or partial shading conditions under agrivoltaics
Implications	Cereal crops not being compatible limits a lot of economic success that could be accessed through agrivoltaics, and could limit implementation to private industry over commercial industry, but could also be popular with citizens and family farms with other crops that can be grown in Germany and with dual income of the system.	As seen in Chile, many fruits already work with agrivoltaics, and Thailand has the opportunity to implement within both private and commercial industry to export come crops while also generating renewable energy, however more work still needs to be done on rice compatibility before implementation can be entirely successful so it serves as a barrier.	Chile has already opened agrivoltaic research centers with fruits like cherry trees, indicating that it is a possibility that they can implement these into the larger commercial market as a top fruit exporter while also meeting their higher renewable energy standards and have private and commercial farms also benefiting from diversified income.
Size of Farms and Farming Attitude			
Results	Almost half of farms in Germany are small, family-operated one or two crop farms, but mainly are located in West Germany while there is an increasing amount of larger farms to increase efficiency in East Germany, and many greening efforts in Germany are geared to medium and large farms which puts smaller farm economic viability at risk.	Thailand operates mostly small family-owned farms that are passed down through generations and have lower productivity as they produce only one or two crops, and the culture is based on subsistence farming meaning there are limited resources for further development outside of commercialization.	Chile has small-scale farms that have smaller production values and need more efficient technology to stay competitive, but there are also large scale commercial farms for more commercialized crops, and both seem open to implementing more renewable energy into agriculture
Implications	German agrivoltaics are currently being studied in both larger and small operations, but are more profitable and successful in smaller areas, so family farms in West Germany can benefit from the increase in productivity and income that is generated, especially because they are at risk due to lower economic viability and productivity	Thailand's lack of resources could serve as a barrier to implementation, especially in rural small farms that have a lack of knowledge about the system, but that could stand to benefit from agrivoltaics and its co-generative crop production and energy income.	Because both seem open to implementation, the fact that both larger and smaller farms are available and agrivoltaics is already being implemented in certain areas, it is encouraging implementation because of open markets and helpful policy.

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Investment and Grid Access			
Results	German renewable energy has lowered costs, created jobs, and has the potential to save billion from imported Russian oil by going fully renewable by 2050, and to do so Germany has invested $89.12 billion USD into clean technology, which was 29% of the European Union's overall investment, and €37 billion to promote improvement of the electricity grid and build wind and solar projects	Thailand has called for $6.8 billion in investments by 2036 to create smart grids and support electricity generation, and has already attracted more than $10.7 billion USD between 2006 and 2018 for renewable energy, as a leader in renewables among ASEAN countries	Chile has seen a 231% increase in year-to-year investment in renewable energy as of 2024 and has generated around $5.7 billion USD to be used in the development of solar and wind projects
Implications	Germany has done a considerable amount in terms of not only providing financial assistance for development of renewable energy, to themselves and others, but also working to improve the grid, which encourages further implementation of agrivoltaics which need funding to continue to be researched and developed and connectivity to the grid.	While it is a good sign that Thailand has raised money and is a leader among ASEAN countries which encourages development, there is still money to be raised and until financial assistance and better grid access is available, there will be barriers to agrivoltaic implementation.	Considering the larger amount of money that has been raised and invested into renewables, there is a large interest in continued development and implementation of renewable systems which can encourage the implementation of agrivoltaics and raise the level of investment given its co-generative draw.
Electricity Generation and Alternative Power Sourcing			
Results	Germany generated 206 TWh of renewable energy between January and September 2024 which exceeds fossil fuels at around 140 TWh, and currently enjoys 59% of its total energy production coming from renewable energy sources.	Thailand has a 18.3% portion of their total energy generation coming from renewables, and has a capacity of 223.3 TWh currently.	Chile currently has 70% of total energy coming from renewable energy generation, with the other 30% coming from fossil fuels, which is up from 51% in 2022 and marking a nearly 20% increase in two years
Implications	Germany has already made a lot of progress in terms of making the majority of its total energy renewable, and there is still more room to grow in terms of pledges that they have made, meaning that this can encourage implementation and that there is room for further development of agrivoltaics	Thailand's renewable energy generation is still very low and could be seen as encouraging for implementation because there is money expected to be coming in in terms of investment and there is room for growth and development to meet the needs of agriculture and renewable energy goals, but this could also be a barrier as development isn't happening as quickly and implementation could be slow if at all in the future.	Chile's renewable energy and commitments have grown considerably faster than most other countries, indicating that there is a good opportunity for implementation, but this could also serve as a barrier to implementation because they are reaching a point where there will not be much more room to grow and develop, and the amount of funding and support could be locked in to other forms of renewable energy.
Threats to Renewable Energy			

Results	Germany's largest sector comes from on and off-shore wind due to the Land-Based Wind Energy Strategy created in 2022 to develop land-based wind capacity to 160 GWh by 2035, but solar is also rapidly expanding and is at 14.9% of energy produced with accelerating grid connection for small systems and remuneration increases.	In Thailand, biomass energy makes up 28.8% of renewable energy production and continues to grow as both renewables and agriculture develop, but they also depend on hydropower which makes up 26.1% and benefits from numerous rivers and lakes in the area, and solar makes up 25.2% that has been successful because of higher solar radiation and long periods of sunlight.	Chile's hydropower makes up 45% of their renewable energy production due to abundant water resources in the South, but is at risk due to melting glaciers and historical droughts, which have led to the development of other renewables like solar, which makes up 34.6% of renewable energy.
Implications	While Germany's wind energy is experiencing a higher level of implementation, with opportunities for further growth near the Baltic and North Seas, solar energy still takes up a considerable amount of total energy production, and with accelerating grid connection and the need for crop protection against adverse weather, implementation of agrivoltaics could see an increase as an option to continue to match the growth of wind energy.	Because biomass energy is a competing energy system to agrivoltaics in terms of its access to and aid in growth of agriculture in Thailand, this could be a barrier to implementation, and because biomass and hydro are already such big sections of small section of total energy production, there might not be enough room to expand to other forms of renewable energy currently.	Solar is a large portion of renewable energy in Chile, and and with hydropower a risk of decrease, there is an opportunity for a solar boom and more growth which can encourage implementation and open the door to other forms of solar energy such as agrivoltaics, which could also help improve agriculture and protect against drought.
		Numbers	
Results	Germany has 6,569 currently operating solar projects, with 10 more proposed and 4 under construction, also with 8 retired plants and zero cancelled projects, and also generated 5 3s (more than any other country) with the RStudio results and 1,137 2s, which also indicated the highest and relatively high amount of agricultural production within the area of solar plants.	Thailand has 430 currently operating solar projects, 6 announced projects, 1 project in construction, and 3 cancelled projects while also had 3 3s and 104 2s within RStudio results indicating high agricultural and solar productivity and activity while entering into a period of rapid renewable expansion in 2025 with a growth rate of 7% expected in 2029.	Chile has 257 operating solar projects, along with dozens announced or in construction, but also has 23 cancelled projects due to increased financial distress and a bottleneck from the grid coordinator that routinely decreased renewable supply to northern regions. Chile also has 4 2s which indicate higher than average agricultural production while being sited near solar activity.
Implications	Along with the growing number of currently operating agrivoltaic facilities in Germany, the amount of solar energy projects and production is an encouragement to further agrivoltaic development, as well as the level of high agricultural productivity from RStudio results.	With entering into a period of renewable energy expansion, and with the high levels indicated in the RStudio results, this can be considered as encouraging implementation because there is an area of high solar production and higher agricultural production and need for protection that can be met with agrivoltaics.	Despite the work that Chile has already done with agrivoltaics, at least in a private sector, the lower level of solar projects and the high number of cancelled projects could be a barrier to implementation, and could suggest issues such as limitations in funding and issues with renewable energy being utilized properly to meet energy pledges.