Optimizing Energy Efficiency Projects in Bangkok Large Commercial Buildings

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ในฐานะที่เป็นผู้มีส่วนสำคัญในการปล่อยก๊าซเรือนกระจกในภูมิภาคเอเชียแปซิฟิก ประเทศไทยได้ให้คำมั่นที่จะลดการปล่อยก๊าซคาร์บอนไดออกไซด์ลง 555 ล้านตันภายในปี 2573 โดยโครงการประสิทธิภาพพลังงานในภาคอาคารพาณิชย์ขนาดใหญ่ ถือเป็นหนึ่งในแนวทางที่สำคัญในการลดการปลดปล่อยมลพิษเพื่อสร้างอนาคตคาร์บอนที่ต่ำลงสำหรับกรุงเทพ นอกจากนี้ โครงการประสิทธิภาพพลังงานยังมีศักยภาพในการลดการใช้พลังงานไฟฟ้า ส่งผลทำให้เกิดการประหยัดพลังงานได้อีกด้วย ด้วยเหตุดังกล่าว งานวิจัยนี้จึงถูกพัฒนาขึ้น เพื่อวัดปริมาณการลดลงของการปลดปล่อยมลพิษ การประหยัดพลังงานกระแสไฟฟ้า และการเพิ่มศักยภาพการประหยัดต้นทุนของโครงการประสิทธิภาพพลังงานแบบต่างๆ สำหรับอาคารพาณิชย์ขนาดใหญ่ในกรุงเทพ โดยจะมุ่งเน้นไปที่การเพิ่มประสิทธิภาพการตัดสินใจในการวางแผนการปลดปล่อยก๊าซคาร์บอนไดออกไซด์ของกรุงเทพในอีกห้าปีข้างหน้า ผลการศึกษาจาก Marginal Abatement Cost Curves ระบุว่า ในบรรดาโครงการประสิทธิภาพพลังงานที่พิจารณาสำหรับอาคารพาณิชย์ขนาดใหญ่นั้น โครงการ LED สามารถลดการปลดปล่อยก๊าซคาร์บอนไดออกไซด์ และมีศักยภาพในการประหยัดพลังงานไฟฟ้าได้สูงที่สุด ในขณะที่การติดตั้ง Chiller และ Air Conditioning กลับมีประสิทธิภาพในเชิงการลงทุนสูงที่สุด สำหรับการวางแผนโครงการด้วย goal programming linear program ยังระบุว่า ประเทศไทยสามารถบรรลุเป้าหมายการปลดปล่อยมลพิษในระยะยาวได้ จากโครงการประสิทธิภาพพลังงานที่พิจารณาข้างต้น

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As a significant contributor to greenhouse gas emissions in the Asia Pacific region, Thailand has pledged to lower its GHG emissions by 555 million tCO_2e by the year 2030. In Bangkok, energy efficiency projects in the large commercial buildings sector are an integral method by which to reduce emissions and to support a lower carbon future. Besides carbon dioxide emissions, energy efficiency projects also have the potential for other benefits including electricity and cost savings. This study develops a methodology to quantify the emissions reduction, electricity savings, and cost savings potential of various energy efficiency methods in this sector, and to optimize decision making in CO2 emissions reduction project planning over the next five years. The study results from Marginal Abatement Cost Curves indicate that among the energy efficiency methods considered for large commercial buildings, LED projects offer the most carbon dioxide emissions reduction and electricity savings potential whereas Chiller and Air Conditioning installations seem to be the most cost effective. Regarding project planning, the goal programming linear program indicates that the current emissions, electricity, and cost savings returns from energy efficiency projects in Thailand are more than sufficient to meet the country's long-term targets.

Field of Study:	Industrial Engineering	Student's Signature ....
Academic Year:	2022	Advisor's Signature ....

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1. Introduction

1.1 Southeast Asia's role in global climate change

Climate change is a pressing issue that has detrimental impacts on many facets of the world, including energy demand, labor productivity, and public health. The gradual increase in global temperatures because of climate change has led to water scarcity, loss of species, increase in extreme weather events, and disease proliferation. Carbon dioxide (CO_2) is the main driver of climate change, as it accounts for almost 80% of greenhouse gas (GHG) emissions. It is widely recognized that to avoid the worst impacts of climate change, the world needs to reduce its CO_2 emissions urgently.

In 2020, the Asia-Pacific region generated 52% of total global CO_2 emissions (17 billion tons) and was the most polluting region in the world (*Bp Statistical Review of World Energy 2020*, 2020). Five of these countries (Indonesia, Malaysia, the Philippines, Thailand, and Vietnam) are in Southeast Asia and collectively account for more than 90% of Asia-Pacific GHG emissions, with land use and deforestation accounting for most emissions. For the rest of this study, CO_2 emissions reduction will be quantified in units of tons of carbon dioxide equivalent, or tCO_2e.

Without mitigation actions, Southeast Asia's rapid emissions growth will continue unabated. Studies by the Asian Development Bank (ADB) show that energy efficiency (EE) gains are the largest long-term sources of emission reductions from 2010 to 2050, while low-carbon alternatives such as biomass fuel and carbon capture also contribute significantly to emissions reduction. The focus of this study henceforth will be on Thailand, including trends in its domestic power market and its approach to managing CO_2 emissions and other energy and cost related benefits.

1.2 Thailand electricity supply and demand trends

Thailand is the second largest economy in Southeast Asia with a GDP that is forecasted to grow 3.5-4.5% through 2025. The growth in Thailand's GDP also resulted in an increase in energy consumption, which has grown an average of 3.5% per year since 2015.

With these trends of increasing GDP and energy consumption, Thailand faces the problem of dwindling energy reserves that may not be able to satisfy increasing domestic electricity consumption over time. According to the Department of Alternative Energy Development and Efficiency (DEDE), energy consumption in Thailand grew more than two-fold over the past 20 years and is expected to increase by almost 6% per year. The Gulf of Thailand oil and gas reserves peaked in 2006 and have decreased since, with a reserve to production ratio of just 5 years, which is the amount of time the reserves will last assuming domestic consumption rates stay the same.

As a result, Thailand is very dependent on energy imports from other countries. As of 2017, the Gulf of Thailand supplied 71% of gas for domestic supply, with 17% imported via pipelines from Myanmar and the remaining 11% importing as LNG from Qatar and Mozambique (*Electricity Generating Authority of Thailand*, n.d.). Over time as the Gulf of Thailand supply decreases, Thailand will need to diversify its fuel sources to decrease reliance on domestic and imported fossil fuels. Additionally, advancements in technologies to increase the efficiency of electricity consumption in various sectors can alleviate some of the strain on domestic resources and can slow the growth in consumption.

Table 1 was reported by the Energy Policy and Planning Office (EPPO) and highlights the percentage share of Thailand's electricity consumption between January and May 2020 for each of its main sectors. Overall, electricity consumption decreased from 2019 to 2020 by 3%, likely due to Covid-19 impacts on travel and work schedules.

Table 1: 2020 Thailand electricity consumption by sector

Sector	***Electricity Consumption, GWh***	***Share, %***
Industrial	82,158	44
Residential	52,860	28
Business	43,950	23
Government and Non-Profit	204	0.1
Agriculture	417	0.2
Other	3,872	2

Note: The above table does not include the electricity consumption of EV charging stations.

Source: EPPO

In 2020, the industrial sector was the key driver of gas demand in Thailand, accounting for 44% of total generation. The industrial sector is energy intensive and includes power plant electricity supply and construction. From 2012 to 2020, the residential sector was the only one that has reported consistent growth, averaging 6% year on year growth. Residential electricity demands include uses such as air conditioning and appliance power.

Another sector to note is the business sector, which accounts for 23% of national electricity consumption. The business sector will be the main sector of interest for the purposes of this study and includes commercial operations such as retail centers, hotels, and office buildings (○ *BOI*, n.d.).

As stated before, to bridge the gap between electricity supply and demand and to ensure sustainable energy development in Thailand, efficiency gains are needed in both energy generation and in consumer end usage. Ways to improve efficiency in the energy supply chain include cutting transportation costs by improving infrastructure and promoting the use of renewables to bolster domestic fossil fuels. Other efficiency gains can also be made at the micro level regarding individual business practices, technology advancements, and customer behavior adaptations. Socioeconomic changes, new trade agreements, and national energy policy updates will also require the country to continually adapt its energy strategy.

1.3 Thailand Power Development Plan

1.3.1 EEDP forecasts

Since 2007, Thailand has prioritized action items to address climate change in its national economic and social development plans. The Power Development Plan (PDP) was prepared by EPPO, a subsidiary of the Ministry of Energy (MOE) and focuses on the priorities of (i) energy security to cope with Thailand's increasing electricity consumption, (ii) economic development, and (iii) reduction of Thailand's carbon footprint from fossil fuels. For the purposes of this study, information from the PDP regarding CO_2 emissions and associated changes to electricity consumption and cost savings will be reviewed (*EPPO Summary Statistic*, n.d.). The PDP was developed for the 2018-2037 time frame and was updated with a revision in 2020. Other EPPO-developed plans include the National Gas Plan, Energy Efficiency Development Plan (EEDP), Alternative Energy Development Plan, and the Oil Plan.

Under the revised PDP, EPPO details plans to reduce the total proportion of energy sources attributed to natural gas, diesel, and coal and to increase alternative energy and imported hydro power in the fuel mix. Of particular interest is the EEDP, which focuses on energy efficiency (EE) targets in various economic sectors to reduce CO_2 emissions and to encourage sustainable energy development in both public and private owned facilities (*CO2 Statistic*, n.d.). The EEDP 5-year budget allocation by economic sectors divided into transportation, industry, and large or small commercial buildings is shown in Figure 1.

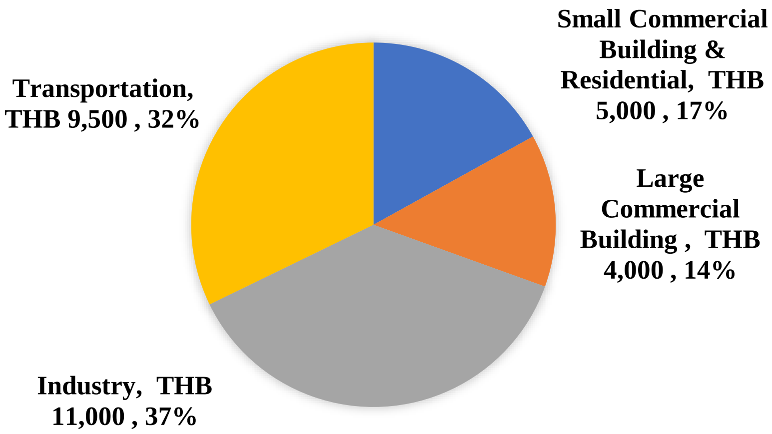


Figure 1: EPPO EEDP 5-year budget by economic sector (in million THB)

Source: EPPO

Not surprisingly due to the sector's large size, the 5-year budget allocation of 11 billion THB for the industrial sector makes up a majority (37%) of the total budget, followed by transportation (32%), small commercial building & residential (17%), and large commercial buildings, or LCBs (14%). The budget is dedicated to implementing EE projects in these sectors to yield positive results in CO_2 emissions reduction and cost savings, the targets of which are shown in Table 2.

Table 2: EPPO EEDP 5-year energy and emissions savings forecasts by economic sector

Sector	***CO_2 Emissions Reduction, million tCO_2e***	***Energy Cost Savings, million THB***
Transportation	4	28,700
Industry	4	17,900
Large Commercial Building	1	3,800
Small Commercial Building & Residential	1	5,300

Source: EPPO

The CO_2 emissions reduction and cost savings targets reflect a similar trend in the 5-year budget allocation, in which the transportation and industrial sectors are expected to yield the highest emissions and cost savings at a combined total of 8 million tCO_2e and 46,600 million THB, respectively. Therefore, these sectors take priority in the EEDP. Specific EE methods that can be used to attain these targets are explained in further detail in Section 1.4.

Major trends to note for Thailand in 2018-2037 are more than doubling of alternative energy and increase in focus on promoting efficient, smart buildings in urban areas. EPPO plans to employ both mandatory and supportive measures in obtaining the targets that it sets in the EEDP, including enforcement of the Energy Conservation Promotion Act and Minimum Energy Performance Standards. Additional measures are the introduction of a Standard Offer Program which provides financial reward for verified energy savings in different locations. Rather than just promote strict incentives, EPPO intends to change market and consumer behaviors to ensure sustainable EE by increasing transparency in energy usage of appliances, buildings, and vehicles.

1.3.2 Thailand's CO_2 emissions reduction efforts

From 2010 to 2020, Thailand averaged about 2% of total Asia-Pacific emissions. In 2020, Thailand reported CO_2 emissions of 277 million tCO_2e with an average annual growth rate of 1.1% between 2010 and 2020, with negative growth in 2019 and 2020 (most likely due to the Covid-19 pandemic as stated before for electricity consumption trends). As part of its commitment to the Paris Agreement, Thailand has pledged a Nationally Determined Contribution (NDC), or CO_2 emissions reduction, of 555 million tCO_2e from 2021 to 2030 (*Thailand and Fossil Gas - Global Energy Monitor*, n.d.). This emission reduction is a 20% reduction from the projected business-as-usual level, assuming no major changes in climate change policies take place.

The Thailand Greenhouse Gas Management Organization (TGO) is the main organization supporting CO_2 emissions reduction initiatives in Thailand (*Greenhouse Gas Mitigation Mechanism)*, n.d.). TGO has programs which support CO_2 emission reduction efforts including the Thailand Voluntary Emission Reduction Program (T-VER), Low Emission Support Scheme (LESS), Joint Crediting Mechanism (JCM), and Clean Development Mechanism (CDM). TGO defines eight project types for CO_2 emissions reductions shown in Figure 2: (1) renewable energy, (2) EE, (3) waste management, (4) renewable energy from waste management, (5) management in transport sector, (6) forests and green spaces, (7) agriculture, and (8) other methods (*GHG TGO Registered Projects*, n.d.).

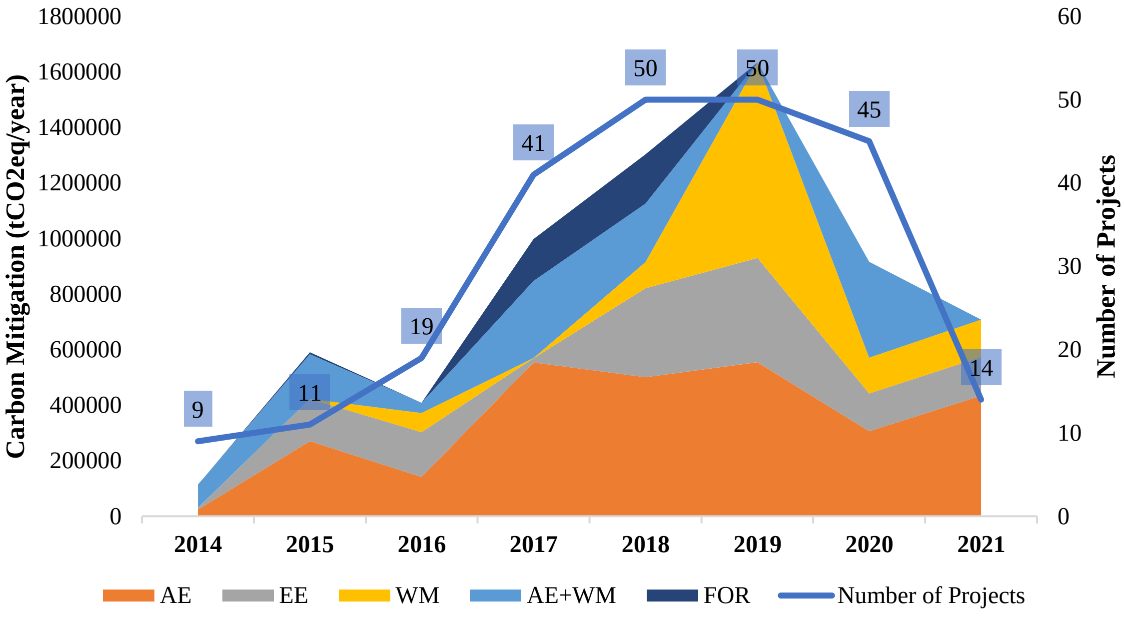


Figure 2: 2014-2021 registered TGO CO_2 emissions reduction projects

Note: The short notation represent the following project types: AE = renewable energy, EE = energy optimization, WM = waste management, AE+WM = renewable energy from waste management, TM = management in transport sector, FOR = forests and green spaces, AGR = agriculture, OTH = other. TM, AGR, and OTH are not shown because they had less than 40,000 tCO_2eq/year in total carbon emissions over seven years.

Source: GHG Mitigation Mechanism

From 2014 to 2021, there have been a total of 240 registered projects with 64 total EE projects. Among the eight project types, EE is the most prevalent and relatively low-cost form of CO_2 emissions reduction in Thailand and consists of methods to minimize energy waste.

EE methods range from large-scale changes such as replacing industrial equipment with more efficient units to small-scale changes such as changing light fixtures to LED and using energy-efficient appliances (*Energy Efficiency | EESI*, n.d.). The total CO_2 emissions reduction potential of the EE projects totals 1.4 million tCO_2e/year out of a cumulative total of 6.7 million tCO_2e/year, accounting for 20% of the total emissions reduction. Using the NDC agreement goal of 555 million tCO_2e total emissions reduction, it would take at least 82 years for Thailand to meet its commitments at the current rate of the TGO projects. Therefore, it is essential that more projects are evaluated and pursued that are efficient in reducing emissions by 2030.

1.4 EE implementation in Thailand's buildings sector

EPPO forecasts that EE projects will result in the highest percentage (57%) of total CO_2 emissions reduction in Thailand by 2030 in accordance with the NDC target. Of this percentage, 52% is EE in end-use cases spanning small commercial and residential, large commercial and residential, and industrial uses.

Many EE projects in Thailand consist of lighting improvement and installations in buildings due to the cost effectiveness and ease of change implementation. Most projects are LED light installations, which are the most prevalent lighting technology on the market. Compared to normal incandescent bulbs, LED bulbs use up to 85% less electricity, resulting in power conservation. There are two major types of LED bulbs: crystalline semiconductor devices and organic LEDs, or OLEDs, which use organic materials (*LED Light Bulbs: Comparison Charts | Eartheasy Guides & Articles*, n.d.).

Besides LED light installations, heating, ventilation, and air conditioning (HVAC) changes are also common. Space heating in commercial buildings mainly consists of using boilers and pipes to heat and to transport water to complete heat transfer radiation through different surfaces. Oftentimes a separate outdoor air system is installed to bring fresh air in to assist with heating processes (*Energy Efficiency | EESI*, n.d.).

Air conditioning involves cooling and removing moisture from air. Larger buildings often use central chillers to assist in producing conditioned air through dehumidification, which consists of condensing water vapor from chilled air and re-heating the air to a desired temperature ("Chapter 5: Increasing Efficiency of Building Systems and Technologies," 2015). Many projects consist of making efficiency improvements to HVAC systems by replacing parts with higher rated efficiencies or by replacing entire units with better heating or cooling technologies. EE measures for buildings are typically categorized according to Table 3.

Table 3: Building EE projects and examples

EE Project Type	***Examples***
Reducing heating demand	Limiting the exposed surface area of the building By selecting efficient heating systems with effective controls
Reducing cooling demand	Providing effective natural ventilation Reducing lighting loads and installing effective lighting controls
Reducing energy requirement for ventilation	Effective window design Using mixed mode ventilation
Reducing energy use for lighting	Making maximum use of daylight while avoiding excessive solar heat gain Installing energy-efficient luminaires with a high light output to energy ratio
Reducing energy use for heating water	Installing time controls, and setting them to correctly reflect the hours of hot water requirement Switching off any associated pumps when hot water is not required

Source: United Nations Industrial Development Organization

Out of these methods for EE project types, the most relevant in Thailand are ‘reducing cooling demand’ and ‘reducing energy use for lighting’. Ways to enforce these EE initiatives include minimum efficiency standards for appliances, design and material building codes, and energy benchmarking for private or public sector buildings.

The commercial building sector has been identified as an area where significant savings can be made because energy demand and consumption in this sector are rapidly growing. In 2020, the third-largest use of electricity after the industrial (44%) and residential (28%) sectors were the business sector (23%). Within the business sector in the Bangkok Metropolitan Area (BMR), office buildings account for 37% of energy consumption amongst large commercial buildings (LCBs). This energy consumption by building type is shown in Table 4 for each type of LCB, while Figure 3 details EPPO's targets to lower the total electricity consumption in LCBs.

Table 4: Share of LCB electricity consumption by building type

Building Type	***Electricity Consumption (GWh)***	***Total Share (%)***
Office Building	7,139	37
Hotel	2,339	12
Hospital	1,172	6
Retail Center	2,351	12

Source: EPPO

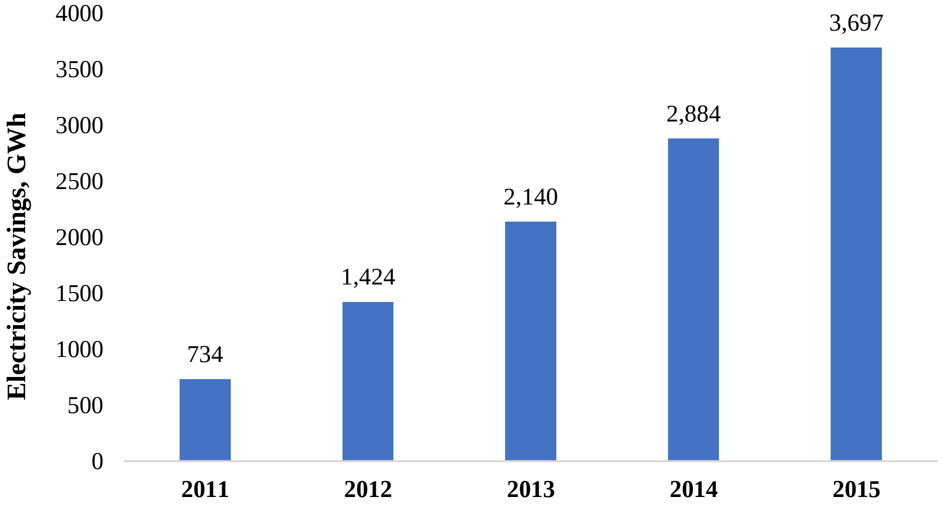


Figure 3: EPPO EEDP cumulative annual targets of electricity savings in LCBs with compound annual growth rate (CAGR) of 38%

Source: EPPO

From 2011 to 2015, EPPO estimated a total electricity savings addition of 2,963 GWh with a 5-year CAGR of 38%. Out of the eight TGO project types, EE is the method most employed in LCBs to meet these goals. We can use this past target to estimate the BMR's electricity savings needs in the next five years (2021-2025), which will greatly contribute to meeting Thailand's 2030 NDC target.

1.5 Problem statement and research objectives

Due to the limited research in EE projects and LCBs, most of the available tools provided by governmental agencies are Excel models, requiring manually updating and having no links to a centralized database. Additionally, previous literature focused on only specific building case studies due to their variations in size, height, and building codes.

Therefore, this study aims to address these gaps by developing tools to standardize EE project comparisons so that they can be fairly assessed for future project development to help meet Thailand's NDC targets. The objective of this study is to create a framework and modeling analysis to study and quantify CO_2 emissions reduction, electricity savings, and cost savings for EE projects in BMR office buildings for the 2021-2025 period.

The main reasons for choosing to study commercial office buildings are access to public information, ease of project implementation and standardization in private CO_2 reduction initiatives, and the fact that commercial plug load is higher than that of the industrial sector, offering more opportunity to mitigate electricity use. The education sector was also disregarded since it consists of the smallest electricity consumption out of those studied.

Furthermore, the study also accounts for electricity savings and cost savings in addition to CO_2 emissions reduction due to dependencies between the different goals and EPPO's targets for each of these factors, which is further discussed in Section 3.

The findings of the study will be used to develop an efficient methodology to optimize project planning for future CO_2 emissions reduction initiatives in Thailand's LCBs and other buildings.

1.6 Scope of study

I propose a thesis to evaluate the feasibility of EE projects focused on lighting installations and HVAC changes in the BMR using publicly available data including but not limited to the TGO project directory, independent company initiatives, and other available resources. Public data will be the study's primary data source because of its accessibility and easier short-term implementation compared to private companies or the industrial and residential sectors.

Ideally, projects of focus will focus on EE projects in LCBs and will include information on all the goals that are of interest to Thailand, including but not limited to CO_2 emissions reduction, electricity savings, and cost savings. The projects will be evaluated for office buildings that fall under the LCB category and will be chosen for as large a sample size as is feasible.

Figure 4 gives a summary of the scope of the study, which consists of sub-categories in order to effectively analyze the available data.

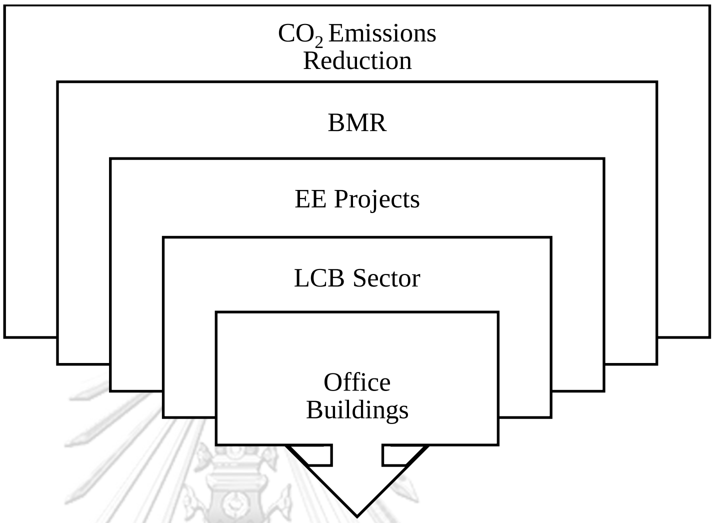


Figure 4: Specific scope of thesis study

1.7 Expected outcome

The study outcome is expected to provide quantitative insight into which EE projects offer the most effective CO_2 emissions reduction and cost savings potential for various LCBs. Furthermore, the findings from further analysis will be evaluated in the medium term to provide a preliminary recommendation for the number of projects to be executed in office LCBs on an annual basis over the next five years.

1.8 Expected benefits

The final recommendations can help advise Thailand's energy planning officials (primarily EPPO) on methods and project planning strategies to meet the country's 2030 NDC agreement. The tools used in this study can also be adapted for evaluation of other projects of interest in sectors such as the small commercial buildings, residential areas, and industrial applications.

2. Literature Review

2.1 CO_2 emissions reduction methods and EE in buildings

CO_2 emissions reduction is not a new objective for policy makers and private enterprises, although now the pressure is stronger than ever for businesses to work towards lowering their share of emissions to meet regulatory, social, and moral obligations. There are many structural and technological investments that can facilitate CO_2 emissions reduction, ranging from the old and established to the new and innovative. These include but are not limited to carbon pricing, smart power grids, fossil fuel plant shutdowns, low carbon technology development, deforestation reduction, charging networks for alternative fuel vehicles, and energy optimization.

According to the ADB, the benefits of emissions reduction from these initiatives include revenues from carbon markets, reduced GHG pollution, environmental preservation, and reduction of other externalities from fossil fuel development such as residential displacement and impact on public health. In its "Southeast Asia and the Economics of Global Climate Stabilization" study, the ADB forecasted that from 2010 to 2100 the benefits from CO_2 emissions reduction in Southeast Asia outweighed the net mitigation costs by 5 to 11 times using a 5% discount rate (Raitzer et al., n.d.). Due to the numerous benefits of GHG mitigation initiatives, Southeast Asian countries have been mobilizing in the past decade to make CO_2 emissions reduction a lasting and impactful reality.

It is crucial to continue emissions reduction earlier rather than later to offset future project costs and to ensure that emissions reduction goals are achieved by target deadlines. For example, the same ADB study showed that a one-year delay in GHG reduction scenarios could increase implementation policy costs by 60% (Koplitz et al., 2017). Considering these findings, Southeast Asian countries which have a significant share of responsibility to reduce CO_2 emissions should proceed with project planning and decision making as soon as possible.

In Southeast Asia, most of the rising electricity consumption is met by coal power, which as shown by the GEOS-Chem chemical transport model could reach high emissions levels and could result in pollution transfer to neighboring regions. These findings also suggests a need for

Southeast Asian countries to coordinate CO_2 emissions reduction efforts, since initiatives in one country are likely to affect the emissions of another that is in close proximity.

Additionally, CO_2 emissions reduction effects vary by sector in each Southeast Asian country. The ADB found that the industrial sector will be the most affected in the Philippines, whereas the agricultural sector and services sector have the greatest impact in Thailand and Malaysia, respectively. For Thailand in particular, Agri-Tech is still in the early stages of development. Therefore, in the case of Thailand it is advisable to concentrate early CO_2 emissions reduction efforts in more developed sectors such as the industrial and commercial sectors.

EE is an integral CO_2 emissions reduction tool that, when combined with other measures, will help to achieve global climate targets as indicated by Figure 5 from the IEA "Energy Efficiency" report. According to the IEA, EE reduces emissions from both the direct reduction of fossil fuel combustion and from the indirect efficiency enhancements in electricity generation.

As evidenced in Figure 5, total CO_2 emissions are significantly higher in scenarios without EE initiatives taking place. Regarding future forecasting, there is also a clear downward trend for an ideal Efficient World Scenario, which accounts for a higher concerted global effort of CO_2 emissions reduction. Rather than decreasing emissions from the norm as has been done until now, the ideal scenario is to lower total emissions over time to create a sustainable solution for climate change and other associated issues.

Figure 5: Energy-related CO_2 emissions with and without EE policies

Note: The figure presents historical data for 2000-2017 (left) and future projections for 2020-2040 (right).

Source: IEA

When employing EE in buildings, it is important to consider that energy consumption is attributed to HVAC (35%), followed by major appliances (18%), lighting (11%), and other items (36%) (Yungchareon & Limmeechokchai, 2004). The building envelope (the walls, foundation, roof, and windows) also plays an important role in overall energy consumption. Chiradeja & Ngaopitakkul evaluated building envelope materials and found that certain combinations of materials that prevent heat loss and promote air flow can reduce energy consumption by up to 65% (Chiradeja & Ngaopitakkul, 2019).

In addition to energy performance, energy efficient materials have high economic feasibility with an internal rate of return (IRR) of 15%. Oftentimes for EE projects in buildings, quantifying cost effectiveness is essential in the decision-making process of whether to initiate a project or not, as most commercial operations have limited budgets that can be allocated to green initiatives. Improving the building envelope is one of many ways where an EE project can yield great savings and can also be cost efficient.

Based on an analysis of ongoing building EE efforts in Thailand, the 2015 DOE "Quadrennial Technology Review" states that there are still large gaps between actual and theoretical enhanced efficiency in equipment performance. Bridging this gap will require advanced manufacturing methods and developments in EE product design to lower costs and to improve quality. A few examples of these R&D opportunities are heat flow tracking tools, increasing accuracy of LED products estimated lifetime, and advanced lighting control systems.

In the case of the LED lighting and HVAC system technology that is of interest to this study, research is still in development to find the most ideal technologies. For example, heat pumps and air conditioners use refrigerants that oftentimes have a high global warming potential when released to the atmosphere. R&D efforts have proved difficult to find substitutes that are non-toxic, have high efficiency, and are relatively low in cost of implementation. The workaround in the meantime is to replace old units with newer models that have better EE specifications while R&D efforts are still underway.

The DOE argues that a combination of EE methods is important to have the highest impact. The study estimates a reduction in commercial cooling and heating by 78% and 77%, respectively, from HVAC EE projects. Furthermore, potentially 81% of commercial lighting energy could be reduced through LED lighting improvements.

2.2 EE impact in Thailand's LCB sector

Through the 1992 Energy Conservation Promotion (ECP) Act, Thailand set specific building EE targets governing lighting, building envelope, and HVAC systems in different types of LCB (Maethasith, n.d.). Over the course of the decade that followed, policy makers and construction project planners had to abide by these guidelines to meet the country's EE goals. These constraints were designed to optimize cost savings and to reduce CO_2 emissions from operation of commercial buildings. Table 5 illustrates the different LCB types and the ECP designated rated power per area to help conserve energy use.

Table 5: ECP allowable rated lighting power density for different LCB types

LCB Type	***Allowable Rated Power per Area (W/m^2)***
Office, education	14
Retail centers	18
Hotels, hospitals, condominiums	12

Source: Thailand Building Energy Code

It is necessary to keep the ECP in mind when designing buildings and when implementing different projects in the commercial sector. Besides abiding by regulatory acts and avoiding legal consequences, following the ECP benefits owners of LCBs from both a cost and from an environmental standpoint.

To effectively analyze and to compare various EE CO_2 emissions reduction methods, it is crucial to define what factors affect LCB electricity consumption patterns. Understanding variations in electricity consumption will allow for more accurate emissions reduction and cost savings values, while also allowing the opportunity for new ideas of electricity conservation efforts to spring to light.

In Bangkok's LCBs, HVAC and LED technologies account for a major of electricity consumption. HVAC systems account for a total of approximately 50-70% of electricity consumption, while newer buildings require more well-lit spaces and therefore have more lighting equipment demand, lowering this share of energy consumption (Chirarattananon & Limmeechokchai, 1994). Older buildings, on the other hand, are usually under-illuminated and did not have lighting standards for how bright interior spaces should be. These kinds of emerging trends will also influence the impact of EE projects on newer buildings and the constraints on what kinds of electrical equipment can be installed and altered due to limits placed on consumption.

The study also focused on the differences in electricity consumption trends across different types of LCB. Building models were developed using data from energy audits to estimate the power demand of future LCBs. Figure 6 shows a comparison of 4 different LCB types (retail centers, offices, hotels, hospitals) and their respective annual electricity consumption rates.

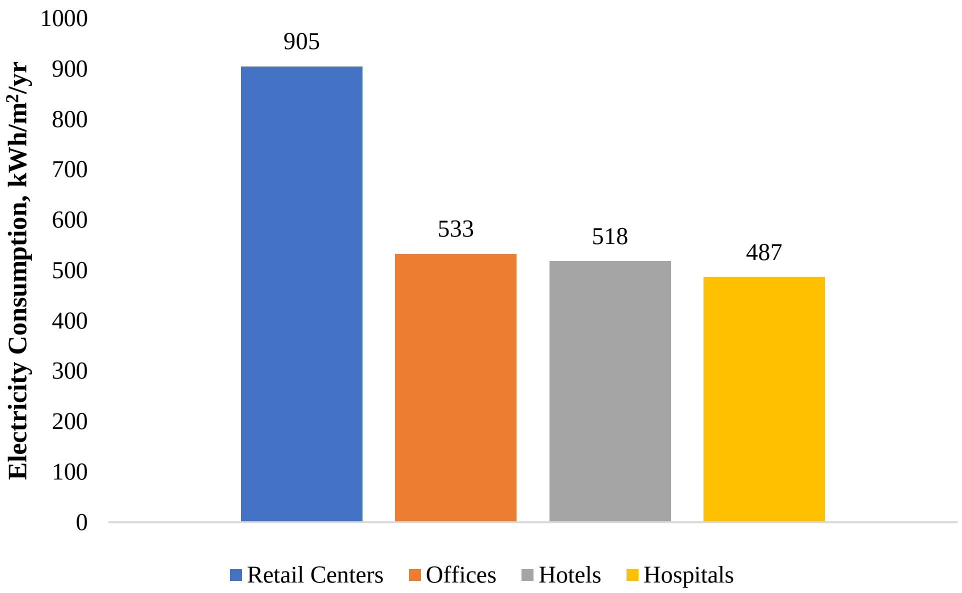


Figure 6: Average electricity consumption by area of each LCB type

As shown above, retail centers dominated in electricity consumption in the study (most likely due to high lighting use from media screens and retail stores), while consumption for offices, hotels, and hospitals were comparable to each other.

Additionally, Yungchareon & Limmeechokchai simulated electricity consumption using a building energy analysis tool called DOE-2 (Yungchareon & Limmeechokchai, 2004). The study reported that the highest electricity consumption savings from EE projects could be found in office buildings and the lowest savings could be found in hospital buildings. Combined with the fact that office buildings consume the second highest amount of electricity (533 kWh/sq m) compared to other LCBs, it can be assumed that this LCB type is an attractive option to implement EE projects in.

Other considerations that affect the electricity consumption rate in LCBs include the building age, height, foundation, shape, heating and ventilation technologies, and construction materials. To illustrate this difference in consumption patterns, a thermal model of a retail center in Ranchi, India showed that certain buildings with differently shaped footprints (such as rectangular shaped, T-shaped, U-shaped, and H-shaped) exhibited greater energy conservation potential. It was found that buildings with L- and H-shaped footprints were most ideal for reducing electricity consumption and for reducing CO_2 emissions reduction.

Similarly, the annual metered electricity consumption of 611 office buildings in England and Wales showed a relationship between electricity consumption and building height (Godoy-Shimizu et al., 2018). The greater the number of stories in a building, the higher the consumption of electricity and CO_2 emissions (137% and 200% increases, respectively). This positive correlation found between increased height, electricity use, and CO_2 emissions is possibly due to taller buildings' increased exposure to strong winds, lower temperatures, and increased sunlight.

With these relationships between building characteristics and electricity consumption in mind, Chirarattananon et al. used Thailand energy audit reports to develop building models for different types of LCBs, identifying common usage hour patterns for each LCB type such as daytime only, late daytime to evening, and 24/7 operating hours. The study identified electricity consumption patterns for the different LCB types (as mentioned before: retail centers, offices, hotels, and hospitals) and classified them by size: large buildings (LB) for 2,000-10,000 sq m and very large buildings (VLB) for anything exceeding 10,000 sq m (Chirarattananon et al., n.d.). For the purposes of this study, electricity consumption patterns for VLBs will be used to assess the EE project potential of different LCBs in the Bangkok region.

Lastly, Chaichaloempreecha et al. assessed the CO_2 reduction potential of energy policies in the Thai LCB sector and found that monetary incentives to support EE projects are the most effective measures to reduce CO_2 emissions (such as the EPPO financial incentives), reducing energy demand by 12% (Chaichaloempreecha et al., 2019). The study also found that LED installations are one of the most effective emissions reducers and that office buildings have the highest reduction potential in the BMR compared to hospitals and hotels, further adding to the line of reasoning for using office LCBs as a preliminary focus of study.

Li et al. found from a survey of 1,287 buildings that the education sector had the smallest electricity consumption per unit area due to shorter opening hours (Li et al., n.d.). Therefore, we disregard education buildings for the purposes of this study.

2.3 Marginal Abatement Cost Curves (MACCs)

In practice, the inconsistencies in policy enactment and the heterogeneity of different building types make widespread EE adoption difficult in Thailand. Therefore, marginal abatement cost curves, or MACCs, standardize EE project parameters on a like-for-like basis and are commonly used by policy makers to compare the viability of various projects that target net-zero energy targets (Huang & Wu, 2021).

MACCs are a decision-making tool widely used to assess and to compare the economic feasibility and CO_2 emissions reduction impact of different reduction strategies (Ibrahim & Kennedy, 2016). A MACC measures two key metrics: (1) CO_2 emissions reduction and (2) Marginal Abatement Cost (MAC), which is the Net Present Value (NPV) of projects per tCO_2e reduced. Both of these key metrics are given in Equations 1 and 2, which also require the knowledge of a project's projected total costs and total savings.

$$MAC = \frac{-NPV}{CO2\ emissions\ reduction\ over\ project\ life} \tag{1}$$

$$NPV = \frac{Total\ project\ costs - Total\ project\ savings}{(1+r)^{project\ lifetime}} \tag{2}$$

Although there are various ways to construct MACCs, a standard method is inputting project parameters including the following:

- Project lifetime
- Total cost of the project (both upfront capital and ongoing operational expenses)
- Expected cost savings to lifetime
- Other considerations (secondary effects, avoided costs of carbon offsets, project dependencies)

The more detail provided for the above parameters, the more accurate the MACC will be in estimating the project's viability.

In addition, MACCs require other information including the local electricity rate and local CO_2 emissions factors, since different countries can have significantly different polices around electricity consumption costs and energy savings estimations. MACCs can also include both technology costs and project implementation costs.

For example, a United States Agency for International Development study in Colombia used both of the aforementioned costs to develop MACCs for LCBs in Colombia, resulting in a CO_2 reduction potential of 45,000 tCO_2e per year in office buildings. The variables that were included as part of the technology and project implementation costs were the total upfront capital expenditure (CAPEX), operating costs, and adoption rates for new and existing buildings in Colombia. It should be noted that lighting (LED) measures were found to be the most important EE project option in the 4 subsectors of the study due to their high CO_2 emissions reduction potential and relatively low cost.

Generally, once a MACC is generated the projects are compared side by side on a bar graph, with the most cost-effective project shown in the left-most column and the least cost-effective project shown in the right-most column. The y-axis shows the value for the project MAC (NPV per ton CO_2 emissions reduction), while the x-axis shows the value for the total CO_2 emissions reduction.

Figure 7 presents an example of a MACC for 6 projects. The projects were assessed by the Western Australia Local Government Association (WALGA) for small-scale EE projects that were implemented in residences and municipal buildings (*Climate Change Templates and Tools | WALGA | WALGA*, n.d.).

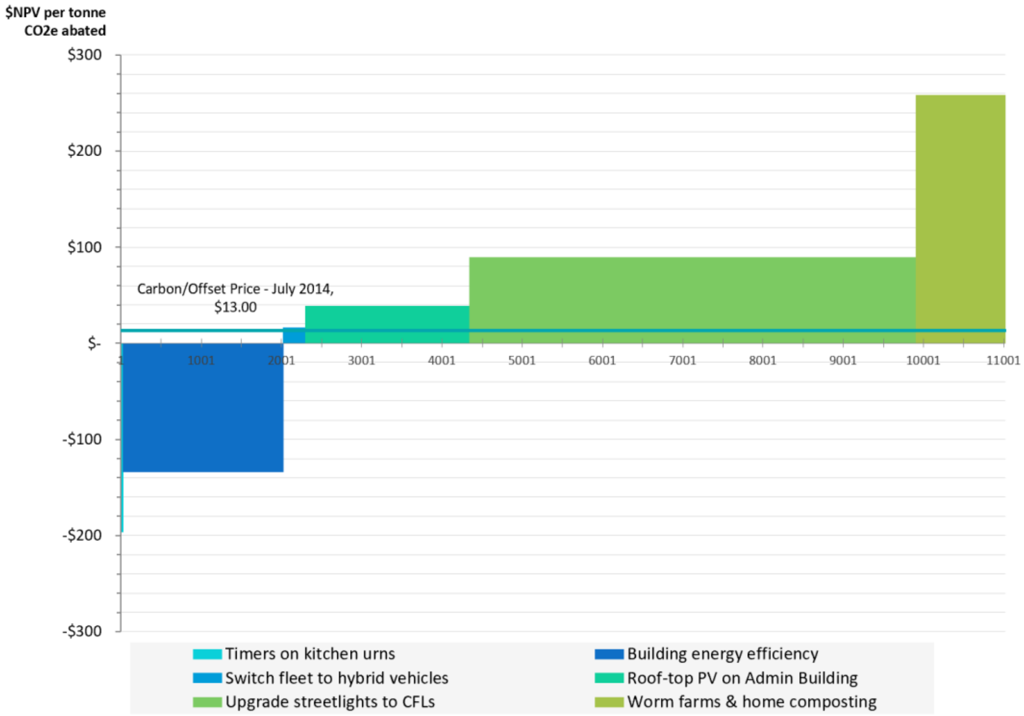


Figure 7: Example of MACC tool to assess small-scale emissions reduction projects

Source: WALGA

Note that some of the EE projects that were studied by WALGA resulted in negative values of NPV per ton CO_2 emissions reduction, indicating that the energy savings are greater than the implementation cost (refer again to Equation 1).

Based on the MACC, the most effective projects to pursue in terms of CO_2 reduction and cost savings potential are the left-most “Timers on kitchen urns” and “Switch fleet to hybrid vehicles” projects, which both report negative MACs. The latter project has a higher CO_2 reduction potential (shown by its larger width on the x-axis), which could make it more favorable depending on the conditions of the study being done and the priorities of the project decision makers.

Normally two types of approaches are used to calculate MACCs, which are static and dynamic. The static method assumes that all CO_2 emissions reduction projects are implemented instantaneously, and that emissions reduction is realized immediately. However, realistically in most cases these changes happen over a longer period and there could be complications that could cause the forecasted results to be altered. More likely than not, theoretical CO_2 emissions reduction estimations that were made at the beginning of a project would be lower than the actual results due to unforeseen circumstances or variables that were not initially accounted for but realized later.

To address these issues, the dynamic MACC construction method accounts for the drawback of the static method, which results in a more realistic comparison of projects over time that may have different rates of implementation. For instance, existing buildings that adopt more efficient appliances would realize CO_2 emissions reduction sooner than buildings that are under construction and planning to adopt the same appliances.

These kinds of differences would be accounted for through discounted costs and baseline values of CO_2 emissions reduction (Gillingham & Stock, 2018). The equation for calculating dynamic MAC to account for changes to initial estimations over time is given in Equation 3.

$$MAC = \frac{C^M - C^B}{E^B - E^M} \tag{3}$$

Note: C and E refer to discounted total costs and total emissions, M and B refer to CO_2 emissions reduction and baseline scenarios, respectively.

Gillingham & Stock used 50 MAC economic studies to compare static and dynamic project costs. As previously stated, the former type of cost occurs over the project lifetime while the latter includes spillovers and addresses the need for long-term fluctuations in the initial project estimates. In one solar panel case study, the researchers found that there was an 'innovation effect' in which solar panel installations in Germany influenced a decrease in solar array prices and increased the social benefits of global solar adoption by 22%.

This positive spillover from one country to the rest of the world was made possible by investments in innovation by the private sector. Therefore, project implementation in the present can influence the options and ease of access to others in the future. This compounded effect is another consideration that is included as part of dynamic MACCs and not static MACCs.

Another consideration to developing MACCs is the default parameters which are used such as the project discount rate. Timilsina et al. utilized dynamic MACCs to investigate CO_2 emissions projects for the building sector in Armenia and Georgia (Timilsina et al., 2016). The results were sensitive to the discount rate; when it was doubled from 7.5% to 15% in the sensitivity analysis, almost all the projects turned to be positive cost options due to the 'safer' estimation and leeway given by the higher rate. Therefore, it is useful to test and compare results for different discount rates while also landing on a number that accurately accounts for individual project risks and rewards.

Besides their application in academic studies, MACCs are also widely used by private companies and international institutions such as McKinsey & Company, Bloomberg, and the World Bank to prioritize climate change mitigation options in various countries. For instance, the McKinsey MAC curve is a comprehensive tool that uses engineering estimates to analyze the costs of various CO_2 emissions reduction technologies and other methods. The World Bank (and the ADB as mentioned before) also use MACCs to assess different countries' CO_2 emissions reduction initiatives and provide recommendations based on the model's findings.

Amongst its various end uses, the MACC curve as a project study tool has its limitations. Even if the MAC is negative, this does not mean that project benefits will be realized right away. There are many technical and financial factors that can add uncertainty to estimated CO_2 emissions reduction potentials such as the accuracy of CO_2 emissions reduction estimations, equipment failure rate, operations and maintenance schedules, varying project costs, and adoption rate of EE projects.

Moreover, engineering estimates and assumptions do not account for behavioral changes over time, such as increased production efficiency and lowered costs from economies of scale. Like the calculation of a dynamic MAC, this knock-on effect can be accounted for using dynamic project costs, which add more layers of complexity to the MACC development process.

2.4 Other CO_2 emissions modeling tools

In addition to MACCs, other tools can be used to assess the potential of different EE projects for CO_2 emissions reduction (and other related benefits such as electricity consumption savings) as well. For example, in one study MACCs for the thermal power sector in 30 Chinese provinces were constructed. A regression analysis was used to find a negative correlation between EE technologies proposed for the provinces and their resulting estimated MAC values (Peng et al., 2018). Therefore, the more EE projects implemented in the region, the greater the return on initial investments.

Results also indicated that CO_2 emissions reduction projects in China's thermal power sector should be employed in the middle Yellow River area and should focus on methods that upgrade equipment efficiency. From this study, it was shown that additional techniques such as regression analysis can lend more insights in addition to the findings from MACCs, such as the optimal location to conduct projects and which sectors are likely to have the greatest impact and should be prioritized.

Other examples include more complex models that take global socioeconomic factors into account as well. Organizations such as the ADB use more sophisticated modeling techniques such as the World Induced Technical Change Hybrid (WITCH) model, which focuses on detailed representation of energy sector innovation, and the Intertemporal Computable Equilibrium System (ICES), which focuses on a more disaggregated depiction of economic sectors. Programming methods (both linear and nonlinear) are also used as supplementary tools to support and to quantify project assessments. With access to models such as these, the ADB can more accurately pinpoint differences in EE project viability and give more confident recommendations to its clients in various countries.

Using the case study of a Pakistani hospital building, Raza et al. explored EE projects in the LCB sector and used Building Information Modeling (BIM) to validate methods for reducing energy waste (Raza et al., 2020). Examples of EE projects in the Pakistani commercial sector includes alterations to materials, glazing, and HVAC systems. As for the model used to quantify the projects, BIM is a cloud-based digital representation of a building asset across its lifecycle that facilitates collaboration between project stakeholders such as architects, engineers and clients and helps to integrate design approaches (Khahro et al., 2021).

Lastly, circling back to the case of Thailand, the Long-range Energy Alternative Planning (LEAP) model is another sector analysis tool that predicts energy consumption, production, and supply for various scenarios. This tool was used to study the NDC potential of renewable energy and energy efficiency projects in Thailand. Recommendations centered around government regulation to incentivize green building development, such as building and structural codes. The focus was also on the mandatory Leadership in Energy and Environmental Design (LEED) Green certification, which is designed to promote the use of energy-efficient building policies that complement the ECP Act.

Using the LEAP model, Misila et al. analyzed CO_2 emissions reduction potential to meet Thailand's NDC target for the period of 2015-2050 (Misila et al., 2020). The findings dictated that to meet the target in time and without delays, the AEDP and EEDP must meet their 2030 targets by at least 50% and 75%, respectively. In the scenario that all EPPO-planned projects are executed, the LEAP model predicted a 30% reduction in CO_2 emissions by 2050 compared to business-as-usual amounts. The 30% reduction was a 10% increase from the NDC target, indicating that if all EE projects are implemented as planned, there should be no obstacles for Thailand to meet its CO_2 emissions reduction obligations. Although this seems promising, delays in project implementation and other obstacles that may impact effective emissions reduction must be accounted for to assess the future accurately.

No matter the chosen method to assess CO_2 emissions reduction projects, other considerations to keep in mind are secondary effects of emissions reduction and project dependencies that may introduce hidden costs to the project. Much of the information associated with CO_2 emissions is based on forecasted data, so it is important to keep uncertainties of the results in mind.

3. Research Methodology

3.1 Methodology outline

First, MACC analysis aimed to provide a general understanding of how effective each EE project type was in terms of cost effectiveness and CO_2 reduction potential. Historical LCB project information was collected from a public source and compiled into a 'project' MACC model. The MACC was used to compare all building types from the public source using comparison metrics of MAC (or marginal abatement cost as stated in Section 2.3) and CO_2 emissions reduction.

Then, these comparison metrics were used to create a 'general' MACC to analyze the different EE projects for an office VLB. For both curves, the EE methods included were LED, AC, and chiller installation (CH). Operating expenditure (OPEX) assumptions and calculations were also completed for the projects. A sensitivity analysis was done for project discount rates of 4%, 8%, and 12%.

Next, Excel optimization aimed to use the findings from the MACC curves to develop a standardized method and recommendation for meeting Thailand's NDC target and EPPO goals in the next 5 years in office LCBs. Office building parameters from the 'project' MACC were converted to a per electricity consumption (kWh) basis. The parameters were CO_2 reduction, electricity savings, and cost savings. These parameters were placed into a goal programming model using the Simplex method, which optimized each of the three objectives by priority. The results indicate the project areas to employ the three different EE methods in office buildings over the next five years. A sensitivity analysis was done for two different goal programming priority scenarios.

Table 6 shows a summary of the information sources used for the methodology, while Figure 8 shows an overview of the overall study methodology.

Table 6: Methodology information sources

Information	***Source***
Registered project emissions and costs	GHGMM project database
Case study project emissions and costs	DEDE PEECB project statistics
CO_2 emissions factors	EPPO
MACC model	WALGA
Electricity rates	MEA
Building statistics	Krungsri Research

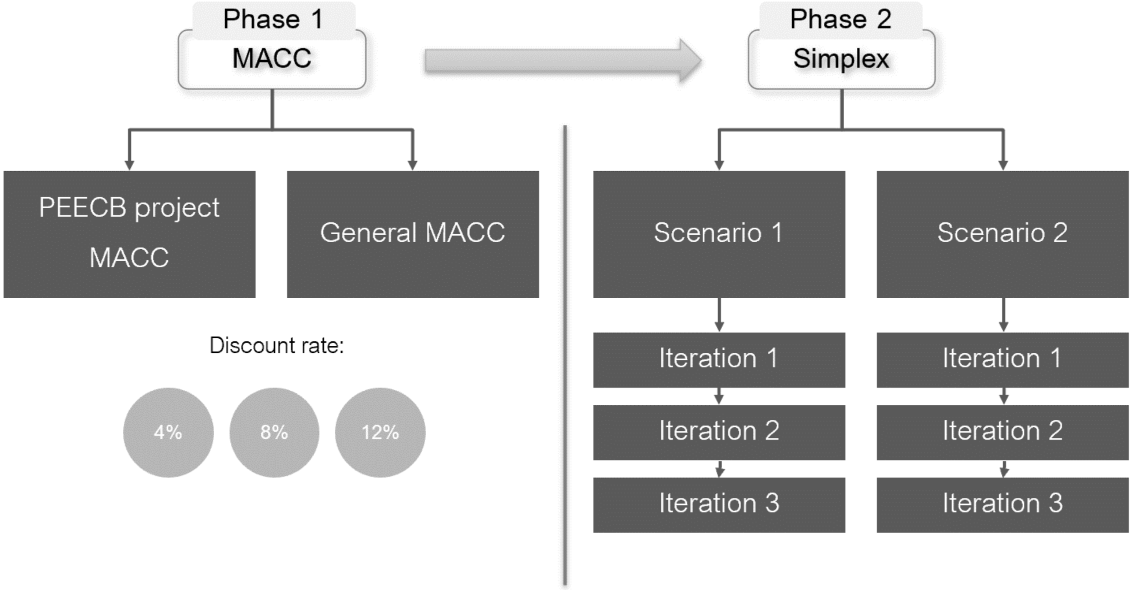


Figure 8: Study methodology outline

Ultimately, the result of the study was a five-year project plan for the period of 2021-2025. The purpose of Phase 1 was to study and to quantify characteristics of EE projects in commercial buildings. The quantified characteristics for office buildings in particular (CO_2

emissions reduction, electricity savings, and cost savings) were then used as inputs to Phase 2 of the methodology. Phase 2 used a goal programming model to develop a project plan for the five-year period; this was done through optimizing the project areas for each EE project type (LED, AC, CH) to employ in office LCBs in the BMR.

3.2 Data collection

3.2.1 Project input parameters

The Department of Alternative Energy Development and Efficiency (DEDE) and the United Nations Development Program (UNDP) initiated the 2014 Promoting Energy Efficiency in Commercial Buildings (PEECB) project, which focused on LCBs in the BMR. The goal of the PEECB project was to promote the use of EE technologies in commercial buildings by increasing awareness of these methods through application and evaluation of policy measures.

Various EE methods were employed in 60 different sites including LED lighting replacement, AC unit optimization, chiller optimization, heater efficiency changes, and building monitoring. For the purposes of this study, only the LED lighting replacement, AC optimization, and CH optimization projects were included in the analysis (Treerutkuarkul et al., n.d.). Figure 9 shows the distribution of building types that were included in the 60 demonstration sites for the PEECB study.

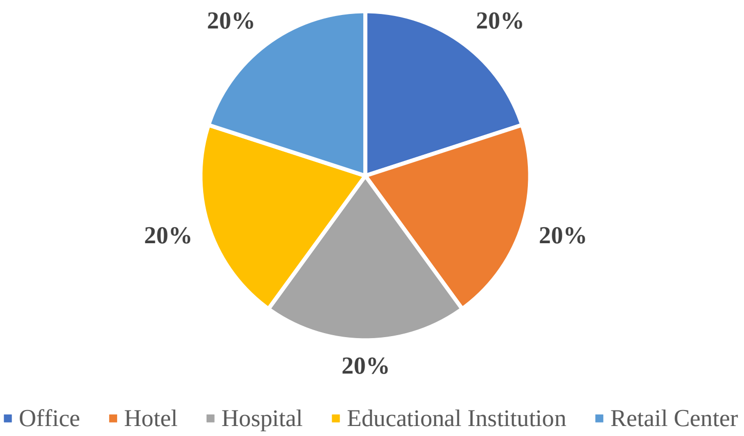


Figure 9: Distribution of buildings in the PEECB EE study

Only 12 buildings included publicly available data for the study purposes, with seven buildings including the information of interest for the EE methods included in this study (shown in Table 7). These building types included offices, hotels, hospitals, and retail centers. The acronyms for the seven LCBs are given in Table 8 (Wong & Worakul, 2018).

Table 7: Twelve PEECB EE project buildings with publicly available information

EE Project	***LED***	***AC Split Type***	***Chiller***	***Heat Pump***
Samrong General Hospital	■	■		
CP Tower 2 & Fortune Town	■	■		
Energy Complex	■	■		
Grand Mercure	■		■	■
Kasikorn Bank			■	
Double A Office			■	
Centara Grand	■			
Aikchol 1 Hospital	■		■	
Aikchol 2 Hospital			■	
Saint Gabriel	■	■	■	
PEA	■	■	■	
Chaweng Garden	■			

Source: DEDE PEECB

Table 8: Acronyms for PEECB demonstration buildings

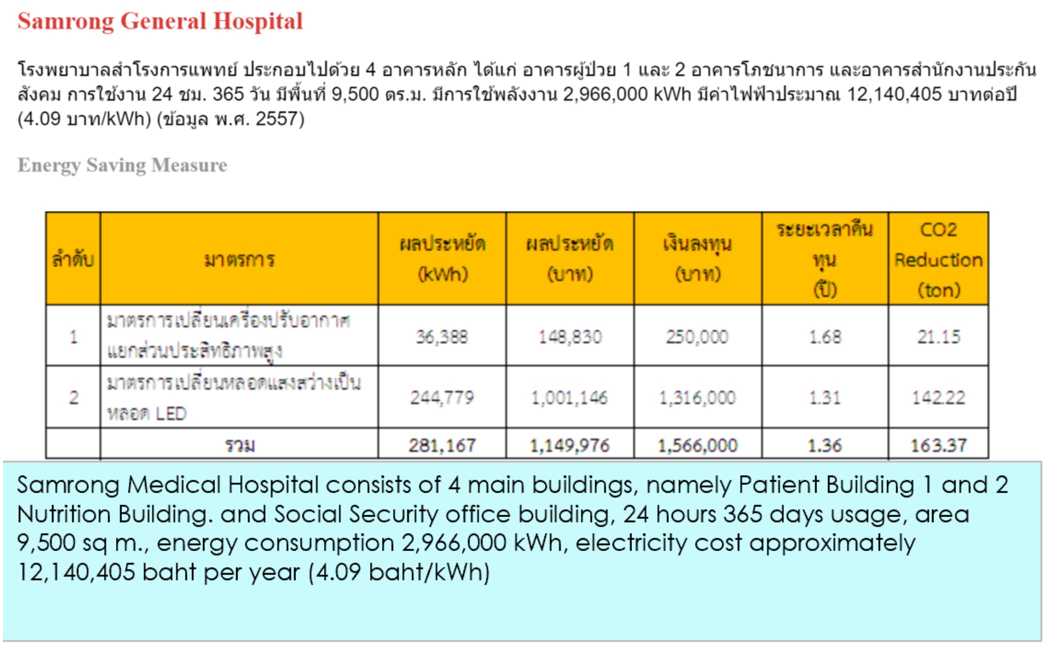
Building Name	***Acronym***
Samrong General Hospital	SR
CP Tower 2 & Fortune Town	CP
Energy Complex	EC
Grand Mercure	GM
Kasikorn Bank	KB
Double A Office	AA
Centara Grand	CEN

Source: DEDE PEECB

Note that the buildings of interest for the purposes of this study include one hospital, two hotels, three offices, and one retail center. The study will use the acronyms from Table 3-3 to refer to each individual building from the PEECB study.

Given data for the PEECB projects included electricity savings, CAPEX, cost savings, CO_2 reduction, and payback period. Characteristics such as the total building area, electricity consumption, and operating hours were also included (Michaud, n.d.).

An example of project information reporting is shown in Figure 10 for the SR building. The PEECB information for the three EE project types is shown in Tables 9, 10, and 11. Refer to Appendix I for an example of the raw project data presentation.



Samrong General Hospital

โรงพยาบาลสำโรงการแพทย์ ประกอบไปด้วย 4 อาคารหลัก ได้แก่ อาคารผู้ป่วย 1 และ 2 อาคารโภชนาการ และอาคารสำนักงานประกันสังคม การใช้งาน 24 ชม. 365 วัน มีพื้นที่ 9,500 ตร.ม. มีการใช้พลังงาน 2,966,000 kWh มีค่าไฟฟ้าประมาณ 12,140,405 บาทต่อปี (4.09 บาท/kWh) (ข้อมูล พ.ศ. 2557)

Energy Saving Measure

ลำดับ	มาตรการ	ผลประหยัด (kWh)	ผลประหยัด (บาท)	เงินลงทุน (บาท)	ระยะเวลาคืนทุน (ปี)	CO2 Reduction (ton)
1	มาตรการเปลี่ยนเครื่องปรับอากาศแยกส่วนประสิทธิภาพสูง	36,388	148,830	250,000	1.68	21.15
2	มาตรการเปลี่ยนหลอดแสงสว่างเป็นหลอด LED	244,779	1,001,146	1,316,000	1.31	142.22
	รวม	**281,167**	**1,149,976**	**1,566,000**	**1.36**	**163.37**

Samrong Medical Hospital consists of 4 main buildings, namely Patient Building 1 and 2 Nutrition Building. and Social Security office building, 24 hours 365 days usage, area 9,500 sq m., energy consumption 2,966,000 kWh, electricity cost approximately 12,140,405 baht per year (4.09 baht/kWh)

Figure 10: Example of PEECB project summary (Samrong General Hospital)

Table 9: PEECB project information for LED installation projects

	SR	***CP***	***GM***	***EC***	***CEN***
Building Type	Hospital	Retail	Hotel	Office	Hotel
Size Type	Large	Very Large	Very Large	Very Large	Very Large
CO2 reduction (t CO2e)	142	22	60	328	572
CAPEX (THB)	1,316,000	144,000	302,950	4,726,372	3,603,560
Electricity savings (kWh)	244,779	37,024	102,955	564,111	984,557
Cost savings (THB)	1,001,146	149,950	394,319	2,256,445	3,564,095
Payback period (yr)	1	1	1	2	1
OPEX (THB)	10,884,884	136,071,904	17,370,980	102,755,556	81,865,772
Area (sq m)	9,500	111,000	33,000	233,000	100,000
Electricity Consumption (kWh/yr)	2,966,000	34,055,000	4,445,700	26,253,000	21,451,000
Operating Time (h/yr)	8,760	4,380	8,760	2,976	8,760

Source: PEECB

Table 10: PEECB project information for AC optimization projects

	SR	***CP***	***EC***
Building Type	Hospital	Retail	Office
Size Type	Large	Very Large	Very Large
CO2 reduction (t CO2e)	21	53	10
CAPEX (THB)	250,000	625,000	443,600
Electricity savings (kWh)	36,388	90,524	17,082
Cost savings (THB)	148,830	366,626	71,744
Payback period (yr)	2	2	6
OM&R (THB)	11,718,448	135,857,904	104,943,672
Area (sq m)	9,500	111,000	233,000
Electricity Consumption (kWh/yr)	2,966,000	34,055,000	26,253,000
Operating Time (h/yr)	8,760	4,380	2,976

Table 11: PEECB project information for chiller optimization projects

	GM	***KB***	***AA***
Building Type	Hotel	Office	Office
Size Type	Very Large	Very Large	Large
CO2 reduction (t CO2e)	306	337	276
CAPEX (THB)	11,225,000	17,740,000	8,145,375
Electricity savings (kWh)	526,200	579,815	347,868
Cost savings (THB)	2,015,350	2,319,260	2,184,648
Payback period (yr)	6	8	4
OM&R (THB)	15,678,000	103,096,740	7,422,576
Area (sq m)	33,000	157,000	6,300
Electricity Consumption (kWh/yr)	4,445,700	26,354,000	2,203,512
Operating Time (h/yr)	8,760	2,808	2,475

Out of all seven LCBs, only EC, KB, and AA are office buildings. Note that it is difficult to compare the project information for the three EE types due to the individual LCB differences in building area, electricity consumption, and annual operating time. Therefore, we choose to continue the study by assessing the CO_2 emissions reduction, electricity savings, and cost savings potential on a per unit electricity consumption basis, which is discussed in Section 3.3. Table 12 shows the electricity consumption for LED, AC/CH, and general office buildings.

Table 12: LCB electricity consumption per unit area by building and project type (rounded to nearest whole number)

	Electricity Consumption (kWh/sq m)
Office building	147
LED	13
HVAC (AC, CH)	115

Source: MEA

The value of electricity consumption on an area basis used for the study was 147 kWh/sq m for office buildings, while for specific EE project types the consumption values were 13 kWh/sq m and 115 kWh/sq m for LED and AC/CH projects, respectively. The different consumption values for different EE project types is due to the equipment associated with each, since LED bulbs consume less energy than HVAC units and cover a greater area in buildings.

3.2.2 CO_2 emissions factor and electricity rate

Other key data that was collected includes Thailand’s electricity rate and annual CO_2 emissions factors. The MEA electricity rate used for MACC calculations was 4 THB/kWh based on a time-of-day tariff rate in 2014. The rate in 2014 was used to reflect the rate when the PEECB project was carried out. Annual CO_2 emissions factors were also taken from EPPO statistics as shown in Table 13.

Table 13: Thailand annual CO_2 emissions factors

	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Emissions Factor ($kgCO_2/kWh$)	0.532	0.507	0.493	0.471	0.459	0.446	0.442	0.421

Source: EPPO

The 2014 emissions factor of 0.532 $kgCO_2/kWh$ was used for the MACC curve development. The emissions factors are required to quantify the amount of CO_2 emitted or saved per unit of electricity generated.

3.2.3 LCB statistics

In addition to the PEECB project information, CO_2 emissions factors, and electricity rates needed to develop the MACC, LCB statistics for the BMR were also required to provide a complete set of inputs for the goal programming model. According to Krungsri Research, the BMR contains 80% of total rentable office space in Thailand where occupancy rates are approximately 94% (*Industry Outlook 2019-2021*, n.d.).

Since our focus is on office buildings, we use the 147 kWh/sq m office building electricity consumption value for the goal programming portion of the study to optimize planning for EE projects in the 2021-2025 period. Other LCB statistics that are necessary for further study include the total LCB area available for use, which is equal to 8,491,500 sq m (*Bangkok Office MarketView Q4 2020 | CBRE Research*, n.d.; Burtenshaw, 2019).

Since only 0.6% of US buildings have earned the Energy Star rating for EE-friendly building design, we assume that the same is true for approximately 0.1% of buildings in the BMR and therefore 99.9% of this LCB area is viable for EE project implementation (*BOT Building Stats*, n.d.).

Figure 11 shows a summary of the inputs and outputs involved in the MACC curves.

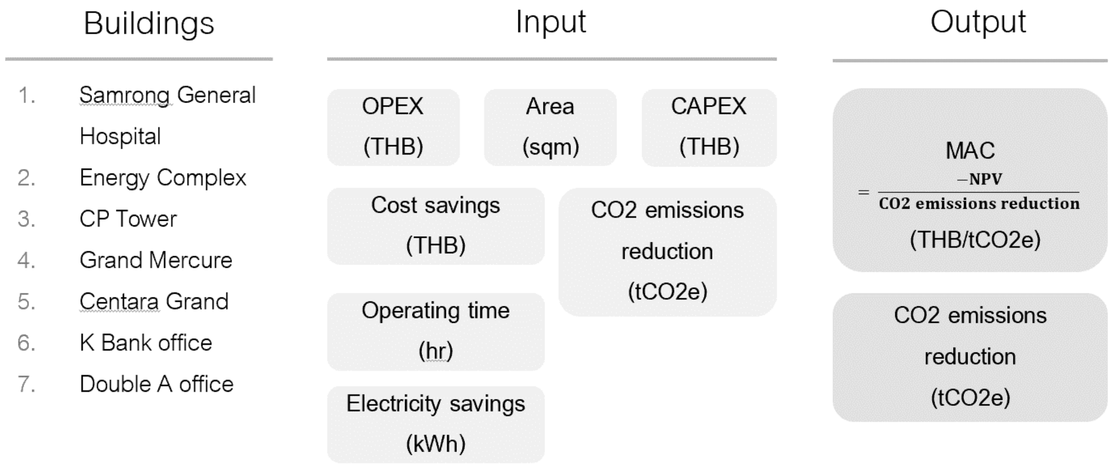
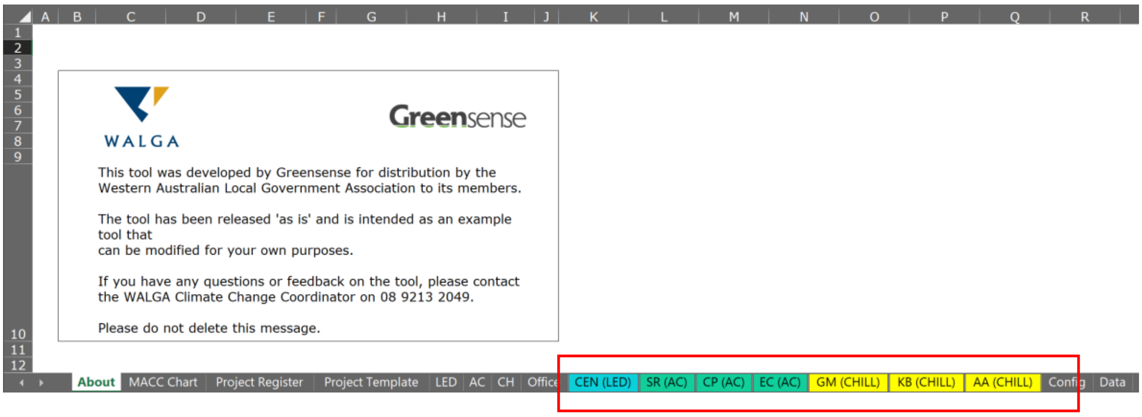


Figure 11: Summary of parameters for PEECB MACC

3.3 Data processing

3.3.1 General MACC development

The PEECB study input parameters, Thailand energy statistics, and LCB statistics were used in the WALGA MACC tool shown in Figure 12.



This tool was developed by Greensense for distribution by the Western Australian Local Government Association to its members.

The tool has been released 'as is' and is intended as an example tool that
can be modified for your own purposes.

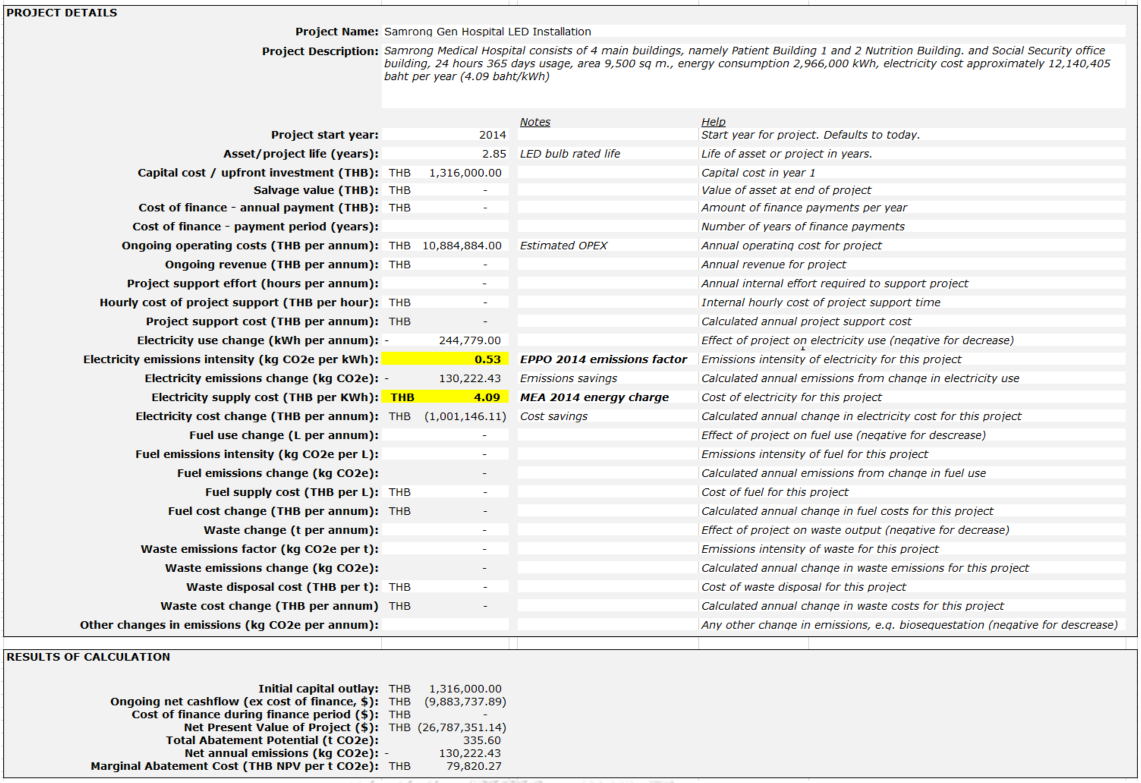
If you have any questions or feedback on the tool, please contact the WALGA Climate Change Coordinator on 08 9213 2049.

Please do not delete this message.

Figure 12: WALGA MACC tool

Source: WALGA

The highlighted Excel tabs contain project information inputs and calculations, while the other tabs provide the MACC curve, project result summaries, and Excel sheet data configurations. All the project tab data is collected into the summary and MACC curve, which include the key MAC and CO_2 emissions reduction parameters as well as information on the project cost and NPV. Figure 13 shows an example of a project tab where the input parameters are entered, and the main MACC outputs are calculated. The ‘Project Details’ section contains all input parameters for MACC development and the ‘Results of Calculation’ section contains the computed net cashflow, NPV, and MAC values.



PROJECT DETAILS

Project Name: Samrong Gen Hospital LED Installation

Project Description: *Samrong Medical Hospital consists of 4 main buildings, namely Patient Building 1 and 2 Nutrition Building. and Social Security office building, 24 hours 365 days usage, area 9,500 sq m., energy consumption 2,966,000 kWh, electricity cost approximately 12,140,405 baht per year (4.09 baht/kWh)*

			Notes	*Help*
Project start year:		2014		*Start year for project. Defaults to today.*
Asset/project life (years):		2.85	*LED bulb rated life*	*Life of asset or project in years.*
Capital cost / upfront investment (THB):	THB	1,316,000.00		*Capital cost in year 1*
Salvage value (THB):	THB	-		*Value of asset at end of project*
Cost of finance - annual payment (THB):	THB	-		*Amount of finance payments per year*
Cost of finance - payment period (years):				*Number of years of finance payments*
Ongoing operating costs (THB per annum):	THB	10,884,884.00	*Estimated OPEX*	*Annual operating cost for project*
Ongoing revenue (THB per annum):	THB	-		*Annual revenue for project*
Project support effort (hours per annum):		-		*Annual internal effort required to support project*
Hourly cost of project support (THB per hour):	THB	-		*Internal hourly cost of project support time*
Project support cost (THB per annum):	THB	-		*Calculated annual project support cost*
Electricity use change (kWh per annum):	-	244,779.00		*Effect of project on electricity use (negative for decrease)*
Electricity emissions intensity (kg CO2e per kWh):		**0.53**	***EPPO 2014 emissions factor***	*Emissions intensity of electricity for this project*
Electricity emissions change (kg CO2e):	-	130,222.43	*Emissions savings*	*Calculated annual emissions from change in electricity use*
Electricity supply cost (THB per KWh):	**THB**	**4.09**	***MEA 2014 energy charge***	*Cost of electricity for this project*
Electricity cost change (THB per annum):	THB	(1,001,146.11)	*Cost savings*	*Calculated annual change in electricity cost for this project*
Fuel use change (L per annum):		-		*Effect of project on fuel use (negative for descrease)*
Fuel emissions intensity (kg CO2e per L):		-		*Emissions intensity of fuel for this project*
Fuel emissions change (kg CO2e):		-		*Calculated annual emissions from change in fuel use*
Fuel supply cost (THB per L):	THB	-		*Cost of fuel for this project*
Fuel cost change (THB per annum):	THB	-		*Calculated annual change in fuel costs for this project*
Waste change (t per annum):		-		*Effect of project on waste output (negative for decrease)*
Waste emissions factor (kg CO2e per t):		-		*Emissions intensity of waste for this project*
Waste emissions change (kg CO2e):		-		*Calculated annual change in waste emissions for this project*
Waste disposal cost (THB per t):	THB	-		*Cost of waste disposal for this project*
Waste cost change (THB per annum)	THB	-		*Calculated annual change in waste costs for this project*
Other changes in emissions (kg CO2e per annum):				*Any other change in emissions, e.g. biosequestation (negative for descrease)*

RESULTS OF CALCULATION

Initial capital outlay:	THB	1,316,000.00
Ongoing net cashflow (ex cost of finance, $):	THB	(9,883,737.89)
Cost of finance during finance period ($):	THB	-
Net Present Value of Project ($):	THB	(26,787,351.14)
Total Abatement Potential (t CO2e):		335.60
Net annual emissions (kg CO2e):	-	130,222.43
Marginal Abatement Cost (THB NPV per t CO2e):	THB	79,820.27

Figure 13: Excel screenshot of PEECB MACC model for one project

Refer to Appendix I for an example of a project summary and more overall detailed information of the MACC results.

3.3.2 Project MACC output

The ‘project’ MACC curve was analyzed for a discount rate of 8%, indicating a moderate level of confidence in the NPV projections due to the relatively short project lifetimes, which were all below 15 years. The discount rate was used to account for the decrease in project value over time and was later used in a sensitivity analysis for the ‘general’ MACC. Generally, higher discount rates suggest higher risk that the future value of the project will be diminished.

Table 14 summarizes the assumptions for both the ‘project’ and ‘general’ MACC curves. As mentioned before, the CO_2 emissions factor and electricity rates are included. Other factors such as project OPEX and duration also needed assumptions since it is not feasible to predict accurate data for future LCB initiatives.

Table 14: MACC assumptions

Project Operating Costs	• The project time span is not long enough to consider replacement or resale costs for the newly installed or changed equipment in each project • OPEX is calculated based on energy usage per year (after electricity savings are accounted for) and the Thailand electricity rate in 2014
Project Duration	• The project lifetime is equal to the average rated life of LED bulbs (2.85 years) in order to standardize project comparisons.
CO_2 Emissions Factor	• 0.53 $kgCO_2$/kWh based on 2014 electricity generation rates and emissions calculations made by EPPO.
EE Electricity Consumption	• LED electricity consumption is 12.9 kWh/sq m and AC/CH electricity consumption is 115.2 kWh/sq m.
Building Envelope	• We do not consider the building envelope (walls, foundation, roof, windows) as part of the study scope.
Building Area	• For the General MACC, a very large building area size of 10,000 sq m was chosen to compare across different EE project types.
Electricity Supply Cost	• 4 THB/kWh based on 2014 MEA electricity supply charge.
Discount Factor	• 4%, 8%, and 12% were used as the MACC discount factors to provide a range for sensitivity analysis.

Additionally, the ‘project’ curve was analyzed for two scenarios: with OPEX and without OPEX. This is to compare the effect that including extra expenditure has on the MACC results and addresses the fact that the PEECB OPEX estimation was quite high compared to the reported CAPEX.

Figure 14 shows the final 'project' MACC curve without OPEX. Note that the MACC curve also includes a carbon offset price of 429 THB/tCO$_2$e from July 2014 that serves as a comparison point. If the MAC value on the y axis is higher than the offset price, it suggests that it may be more economically viable to purchase offsets rather than to pursue the project. However, policy makers may choose to pursue a project for many reasons other than cost effectiveness.

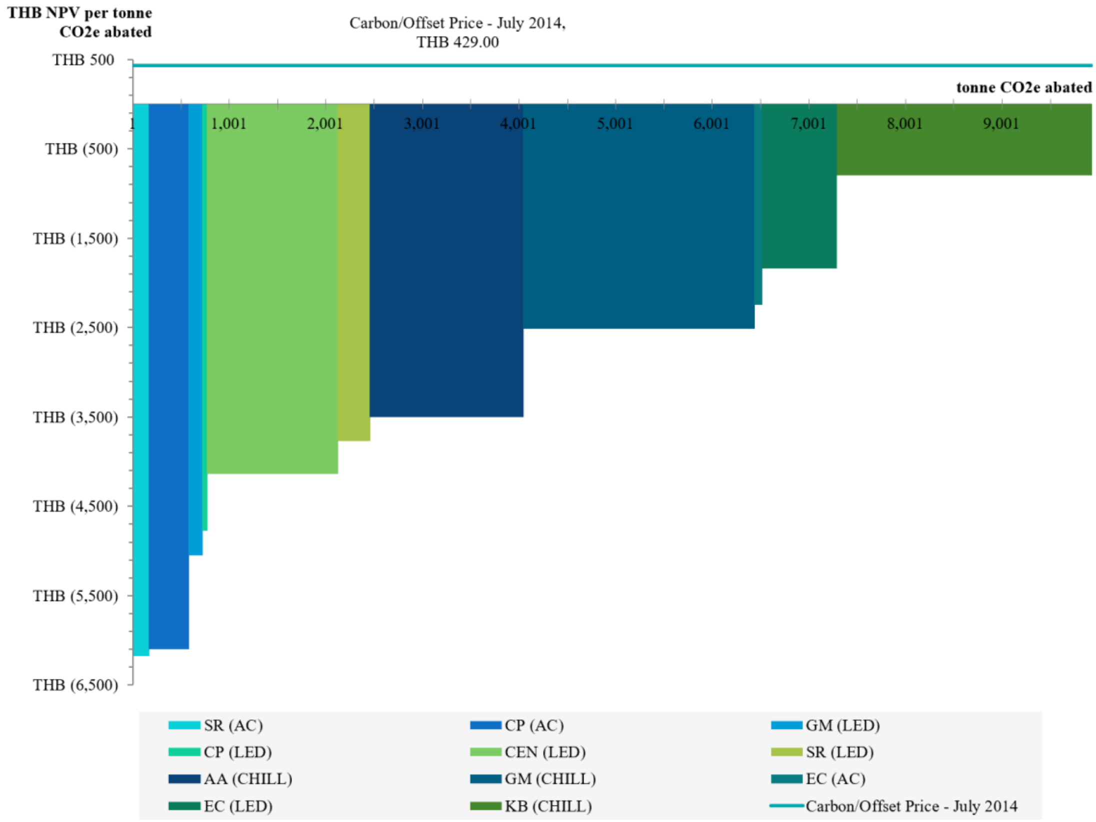


Figure 14: PEECB project MACC curve (discount rate = 8%, no OPEX)

The average project lifetime for LED projects was 2 years, while for AC and CH projects was 15 years. This is due to the short-lived nature of lightbulbs which need replacement compared to larger HVAC units which can be repaired and maintained. Except for one project from each EE type, the ‘project’ MACC curve suggests that AC and LED projects were the most cost effective compared to CH projects in the PEECB study. This is shown by the two AC and three LED projects being closest to the left side of the curve, with more negative values indicating a greater return on their initial investment. The higher negative values also indicate that for every THB invested in the projects, more CO_2 emissions were reduced. In regards to CO_2 emissions reduction, the CH projects showed the highest reduction as shown by the larger width of the columns.

Table 15 summarizes the findings in ranges from the two MACC curves for the PEECB projects.

Table 15: Summary of CO_2 emissions reduction and MAC findings for PEECB project MACC curves

	CO_2 emissions reduction (tCO₂e)	***MAC (THB/tCO₂e)*** *No OPEX*	***MAC (THB/tCO₂e)*** *Including OPEX*
LED	51 – 1,350	(5,053) – (1,840)	80,000 – 6,900,000
AC	78 – 412	(6,179) – (2,248)	599,000 – 11,500,000
CH	1,584 – 2,640	(3,505) – (800)	37,000 – 333,000

For the ‘no OPEX’ and ‘including OPEX’ scenarios, the CO_2 emissions reduction remains the same since the scenarios only affect the cost outlook for the projects. The main difference in MAC values is that for the ‘no OPEX’ scenario, the values are negative whereas for ‘including OPEX’ they are positive since they account for significant added cost.

In terms of trends, as stated before CO_2 emissions reduction was highest for the PEECB CH projects and was lowest for the AC projects overall. For the ‘no OPEX’ scenario, however, the CH projects are the least cost effective with the least negative MAC range, while for the 'including OPEX' scenario the CH projects are the most cost effective with the most negative MAC range. This is due to the relatively higher OPEX for the CH projects that was reported in the PEECB study.

Overall, from the PEECB results, AC projects were the most cost effective for the 'no OPEX' scenario, while CH projects were most cost effective for the 'including OPEX' scenario. CH projects showed the highest range of CO_2 emissions reduction as well.

3.3.3 General MACC inputs

Although the data includes the four LCB types, office buildings were chosen to be the focus of this study due to their high prevalence and 37% share of electricity consumption. Table 16 summarizes the inputs to the 'general' MACC that focuses on office LCBs.

Table 16: Summary of CO_2 emissions reduction, CAPEX, and electricity savings inputs to 'general' MACC

	CO_2 emissions reduction (tCO_2e)	***CAPEX (THB)***	***Electricity savings (kWh)***
LED	14	202,849	24,211
AC	0.43	19,039	733
CH	438	12,929,167	552,171

These inputs were calculated by finding the parameter value per area of individual PEECB office buildings (EC and AA buildings) for each EE type. Then, the parameter value per area (tCO_2e/sq m, THB/sq m, kWh/sq m) were multiplied by a VLB area of 10,000 sq m. Since this method focuses on individual PEECB buildings and is difficult to establish a general trend, the purpose is to isolate differences between the EE project types in office buildings.

Clearly, each of the EE types have different tradeoffs that are further discussed in Section 4. The office chiller project shows the highest CO_2 emissions reduction and electricity savings, but also incurs the highest CAPEX. On the other hand, the AC project is lowest in CO_2 emissions reduction and electricity savings and incurs the lowest CAPEX. Further trends about NPV and MAC for the 'general' MACC are discussed in Section 4.

Each type of EE project required calculation of OPEX to accurately account for total project costs.[1] The project OPEX was estimated based on electricity cost and consumption according to Equation 4, where r_e equals electricity rate (4 THB/kWh), A equals building area (sq m), and E equals electricity consumption (kWh/sq m). Refer to Table 17 for a summary of OPEX estimations for the EE methods.

$$OPEX_{LED} = r_e \times A \times E \tag{4}$$

Table 17: OPEX values for 'general' MACC EE projects

	OPEX calculation	***OPEX value (THB/yr)***
LED	4 x 10,000 x 12.9	514,800
AC	4 x 10,000 x 115.2	1,290,240
CH	4 x 10,000 x 115.2	1,290,240

The estimated project OPEX was added to CAPEX to input the total cost for each EE project type in the 'general' MACC. The electricity consumption for LED and AC/CH projects

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[1] The PEECB project information was already pre-calculated by DEDE and verified for use in the study. Values that required additional calculation included the OPEX and other assumptions for LCB area and EEDP targets that are later specified in the goal programming model constraints.

are different due to the different rated energy requirements of LED bulbs and HVAC units. The respective electricity consumption for LED and AC/CH as stated before are 12.9 kWh/sq m and 115.2 kWh/sq m, respectively.

Figure 15 shows another representation of the overall study methodology with the summarized outputs from Phase 1 (CO$_2$ emissions reduction per kWh, electricity savings per kWh, cost savings per kWh, and total office LCB area). The outputs are used as inputs in Phase 2, which produce the final insights of the study for the period 2021-2025 (total CO$_2$ emissions reduction, total electricity savings, and total cost savings).

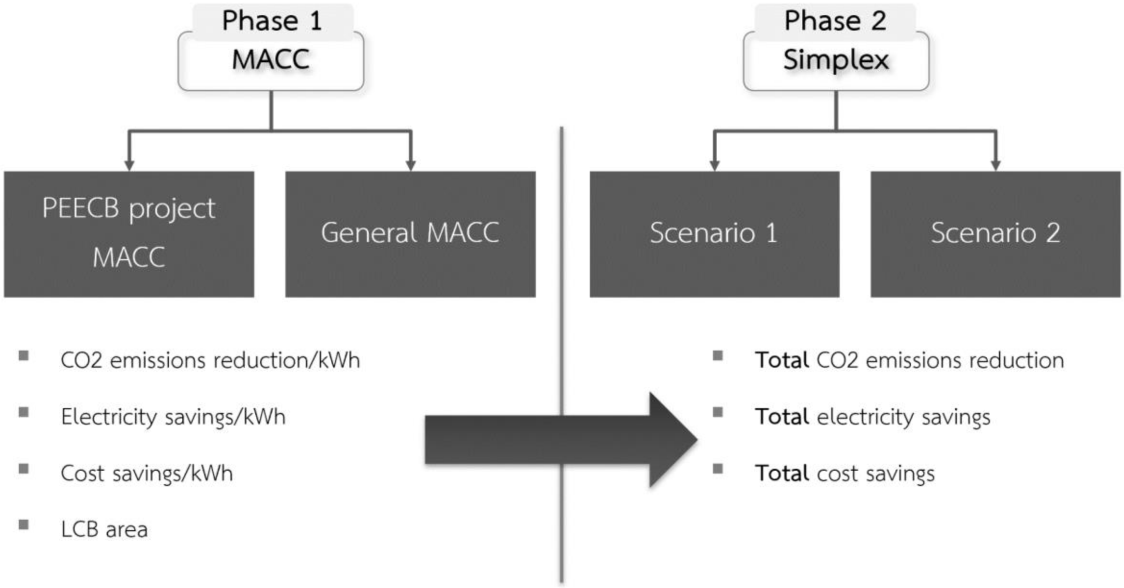


Figure 15: PEECB project MACC curve (discount rate = 8%, no OPEX)

3.3.4 Goal programming model inputs

For the study's final analysis, the Simplex linear program method was used to designate the office building area to be used in each EE project in the 5-year period for 2021-2025. The linear program was designed and written for the purposes of this study to create a general quantitative framework by which to plan EE projects in the chosen area of office LCBs.

To set the parameters for the goal programming model, the total EEDP CO_2 emissions reduction, electricity savings, cost savings, and budget targets were adjusted to reflect office building share of electricity consumption (i.e., 37%). These inputs were then written into equations that were used to define the goal programming model values (*Performing a Goal Programming Analysis Using CPLEX*, 2014). The modified values for the input parameters are shown in Table 18.

Table 18: Parameters from 'project' MACC used as goal programming model inputs

Project Type	**CO_2 Reduction (tCO_2e/kWh)**	**Electricity Savings (GWh/kWh)**	**Cost Savings (THB/kWh)**	**CAPEX (THB/kWh)**
LED	2.6×10^{-3}	4.4×10^{-6}	1.8×10^{1}	8.4×10^{-4}
AC	3.1×10^{-5}	5.3×10^{-8}	2.2×10^{-1}	3.3×10^{-4}
CH	8.6×10^{-4}	1.1×10^{-6}	7.1×10^{3}	3.4×10^{-4}

From the 'project' MACC, the parameters were converted to an electricity consumption basis to standardize comparisons between office locations with different characteristics. Equation 5 shows how each of the parameters were calculated from the PEECB project data for the LED project with electricity consumption 13 kWh/sq m. The PEECB office parameter value (with units of tCO_2e, GWh, THB) is multiplied by the inverse of the VLB area (10,000 sq m) and the EE project electricity consumption rate.

$$Simplex\ input\ parameter = PEECB\ parameter \times \frac{1}{10{,}000\ sq\ m} \times \frac{1}{13\ kWh/sqm} \tag{5}$$

In addition to the values in Table 15, Thailand's EPPO EEDP targets for electricity savings, CO_2 emissions reduction, cost savings, and total budget were used as constraints for the goal programming model. Table 19 shows a summary of these values that were used as inputs to the model.

Table 19: EPPO EEDP adjusted CO_2 emissions reduction, electricity savings, cost savings, and budget targets for office buildings

Year	***2021***	***2022***	***2023***	***2024***	***2025***
Annual Electricity Savings (GWh)	538	742	1,025	1,414	1,951
5-year LCB CO2 reduction (tCO_2e)	$3.7x10^5$				
5-year cost savings (THB)	$1.4x10^9$				
5-year budget (THB)	$1.48x10^9$				

Source: EPPO

Based on these numbers, the decision variable of area of project work for each EE project type was chosen to standardize the model results as much as possible, since it is hard to quantify project targets for buildings otherwise. The optimal area for each EE project type for each year is then categorized into office buildings by large (LB) and very large (VLB) size buildings depending on their square footage.

Table 20 shows a summary of goal programming linear model inputs, while Table 21 shows a detailed summary of the inputs which has detailed equations for each of the Simplex program parameters.

Table 20: Goal programming model inputs summarized descriptions

Parameters	Electricity use by project type
	CO2 emissions reduction
	Electricity savings
	Cost savings
	Total cost
Decision Variable	Office project building area per year per EE project type
Objectives	Maximize CO2 emissions reduction
	Maximize electricity savings
	Maximize cost savings
Constraints	Office area available
	EEDP budget
	EEDP CO2 target
	EEDP electricity target
	EEDP cost savings target
	Forecasted project annual growth

Table 21: Goal programming model detailed variables and equations

Decision Variables	**Area of project work**	Let y_{ij} = the area of EE work done in each EE project type i in year j where i = {LED,AC,CH}, j = {1,2,3,4,5} where x_{ij} >= 0 where j = {1,2,3,4,5}
Objectives	**Maximize 5-year CO_2 reduction**	Z_1 = Office LCB electricity consumption x Area x Average CO_2 emissions reduction $Z_1 = 146.4$ x $[(2.5x10^{-3}y_{LED1} + 3.1x10^{-5}y_{AC1} + 8.6x10^{-4}y_{CH1}) +$ $(2.7x10^{-3}y_{LED2} + 3.2x10^{-5}y_{AC2} + 9.0x10^{-4}y_{CH2}) +$ $(2.8x10^{-3}y_{LED3} + 3.4x10^{-5}y_{AC3} + 9.4x10^{-4}y_{CH3}) +$ $(2.9x10^{-3}y_{LED4} + 3.6x10^{-5}y_{AC4} + 9.9x10^{-4}y_{CH4}) +$ $(3.1x10^{-3}y_{LED5} + 3.7x10^{-5}y_{AC5} + 1.0x10^{-3}y_{CH5})]$
	Maximize electricity savings	Z_2 = Office LCB electricity consumption x Area x Average electricity savings $Z_2 = 146.4$ x $[(4.4x10^{-6}y_{LED1} + 5.3x10^{-8}y_{AC1} + 1.1x10^{-6}y_{CH1}) +$ $(4.6x10^{-6}y_{LED2} + 5.6x10^{-8}y_{AC2} + 1.1x10^{-6}y_{CH2}) +$ $(4.8x10^{-6}y_{LED3} + 5.8x10^{-8}y_{AC3} + 1.2x10^{-6}y_{CH3}) +$ $(5.1x10^{-6}y_{LED4} + 6.1x10^{-8}y_{AC4} + 1.3x10^{-6}y_{CH4}) +$ $(5.3x10^{-6}y_{LED5} + 6.4x10^{-8}y_{AC5} + 1.3x10^{-6}y_{CH5})]$

Maximize cost savings Z_3 = Office LCB electricity consumption x Area x Average cost savings

$$Z_3 = 146.4 \times [(18y_{LED1} + 0.22y_{AC1} + 7047y_{CH1}) + (18y_{LED2} + 0.23y_{AC2} + 7399y_{CH2}) + (19y_{LED3} + 0.25y_{AC3} + 7769y_{CH3}) + (20y_{LED4} + 0.26y_{AC4} + 8157y_{CH4}) + (21y_{LED5} + 0.27y_{AC5} + 8565y_{CH5})]$$

Constraints

5-year LCB CO_2 reduction

$$146.4 \times [(2.5\times10^{-3}y_{LED1} + 3.1\times10^{-5}y_{AC1} + 8.6\times10^{-4}y_{CH1}) + (2.7\times10^{-3}y_{LED2} + 3.2\times10^{-5}y_{AC2} + 9.0\times10^{-4}y_{CH2}) + (2.8\times10^{-3}y_{LED3} + 3.4\times10^{-5}y_{AC3} + 9.4\times10^{-4}y_{CH3}) + (2.9\times10^{-3}y_{LED4} + 3.6\times10^{-5}y_{AC4} + 9.9\times10^{-4}y_{CH4}) + (3.1\times10^{-3}y_{LED5} + 3.7\times10^{-5}y_{AC5} + 1.0\times10^{-3}y_{CH5})] >= \mathbf{370{,}000}$$

5-year LCB cost savings

$$146.4 \times [(18y_{LED1} + 0.22y_{AC1} + 7047y_{CH1}) + (18y_{LED2} + 0.23y_{AC2} + 7399y_{CH2}) + (19y_{LED3} + 0.25y_{AC3} + 7769y_{CH3}) + (20y_{LED4} + 0.26y_{AC4} + 8157y_{CH4}) + (21y_{LED5} + 0.27y_{AC5} + 8565y_{CH5})] >= \mathbf{1.4\times10^{9}}$$

Annual LCB electricity savings	146.4 x $(4.4x10^{-6}y_{LED1} + 5.3x10^{-8}y_{AC1} + 1.1x10^{-6}y_{CH1}) >=$ **538 GWh** 146.4 x $(4.6x10^{-6}y_{LED2} + 5.6x10^{-8}y_{AC2} + 1.1x10^{-6}y_{CH2}) >=$ **742 GWh** 146.4 x $(4.8x10^{-6}y_{LED3} + 5.8x10^{-8}y_{AC3} + 1.2x10^{-6}y_{CH3}) >=$ **1,025 GWh** 146.4 x $(5.1x10^{-6}y_{LED4} + 6.1x10^{-8}y_{AC4} + 1.3x10^{-6}y_{CH4}) >=$ **1,414 GWh** 146.4 x $(5.3x10^{-6}y_{LED5} + 6.4x10^{-8}y_{AC5} + 1.3x10^{-6}y_{CH5}) >=$ **1,951 GWh**
5-year EPPO EEDP budget	146.4 x $[(8.4x10^{-4}y_{LED1} + 3.3x10^{-4}y_{AC1} + 3.4x10^{-4}y_{CH1}) +$ $(7.9x10^{-4}y_{LED2} + 3.1x10^{-4}y_{AC2} + 3.3x10^{-4}y_{CH2}) +$ $(7.5x10^{-4}y_{LED3} + 3.0x10^{-4}y_{AC3} + 3.1x10^{-4}y_{CH3}) +$ $(7.2x10^{-4}y_{LED4} + 2.8x10^{-4}y_{AC4} + 3.0x10^{-4}y_{CH4}) +$ $(6.8x10^{-4}y_{LED5} + 2.7x10^{-4}y_{AC5} + 2.8x10^{-4}y_{CH5})] <=$ **$1.48x10^{9}$**
BMR office area available	$\sum y_{kj} <= 8,491,500$
Less than 37% project area growth	$y_{k(j+1)} <= 1.37y_{kj}$
More than 10% project area growth	$y_{k(j+1)} >= 1.10y_{kj}$

AC projects >= 0.5 CH projects	$y_{ACj} >= 0.5y_{CHj}$
Non-negativity	$y_{kj} > 0$

Note: The equations shown in the table were included as part of the goal programming model using the Simplex method in the Excel file.

From Table 21, each input parameter has different calculation values for each year in the period 2021-2025 since a key assumption is that the projects increase in efficiencies of CO_2 emissions reduction, electricity savings, and cost savings. Regarding the constraints related to the objectives, the electricity savings target is the only one separated by year.

Additionally, Table 22 lists out the assumptions for the goal programming model. The assumptions cover each of the constraints in regard to the EEDP targets and also specify assumed efficiency gains and increases in project area every year.

Table 22: Goal programming model assumptions

CO_2 Emissions Reduction Target	• The 5-year target is based on 37% of the EEDP target for LCB's (370,000 tCO_2e)
Cost Savings Target	• The 5-year target is based on 37% of the EEDP target for LCB's ($1.41x10^9$ THB)
Electricity Savings Annual Target	• 2021-2025 targets forecasted based on the EEDP 2011-2015 CAGR of 38%
Budget	• The 5-year target is based on 37% of the EEDP target for LCB's ($1.48x10^9$ THB)
Efficiency Constraints	• Annual increase of 5% in each parameter (CO_2 emission reduction, electricity savings, cost savings) and decrease of 5% in project cost
Office Electricity Consumption	• Average electricity consumption is used instead of variable load profile (146.4 kWh/sq m)
BMR Office Buildings	• Use a BMR available area of 8.5 million sq m (Q1 2021) • 0.6% of US buildings earned Energy Star, therefore assume 0.1% of office space in BMR are unavailable for EE project implementation
Goal Programming	• Degradation in increments of 5% is acceptable for objectives descending in priority
AC/CH Project Dependency	• Due to being part of the same HVAC unit, AC projects >= 0.5 CH projects
Project Annual Growth	• Annual project area growth rate >10%, <37%

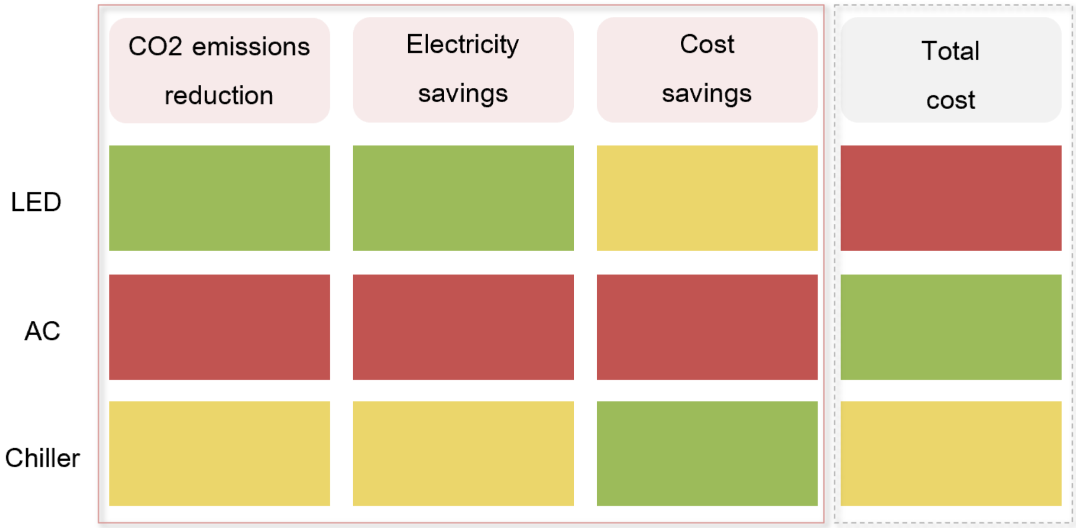
Preemptive goal programming was used to weigh the three linear programs associated with each objective differently based on their priority, with an allowable 5% degradation in objective values with each iteration. Using this method of goal programming, objectives with higher priorities are slightly degraded to find the optimal solutions for lower priority objectives. In Equation 5, G_1 represents the highest priority objective, which in this case is maximizing CO_2 emissions reduction. The linear program is written to solve for G_1 first, resulting in an optimal solution of Z_1.

$$G_1 = Z_1 \tag{5}$$

This objective is then added on as a constraint to the next Simplex method iteration for G_2. Each successive model consists of an extra constraint and allowable percentage degradation that is expressed as an inequality shown in Equation 6.

$$G_1 <= 1.05 \times Z_1 \tag{6}$$

In the preemptive goal programming set for the different objectives, there is potential conflict between objectives such as maximizing CO_2 emissions reduction and maximizing cost savings, since a higher emissions reduction does not necessarily correlate with higher saved costs. This is shown in Figure 16 for each of the EE projects for office LCBs.



	CO2 emissions reduction	Electricity savings	Cost savings	Total cost
LED	🟩	🟩	🟨	🟥
AC	🟥	🟥	🟥	🟩
Chiller	🟨	🟨	🟩	🟨

Figure 16: Visual representation of the conflict of objectives between each EE project type

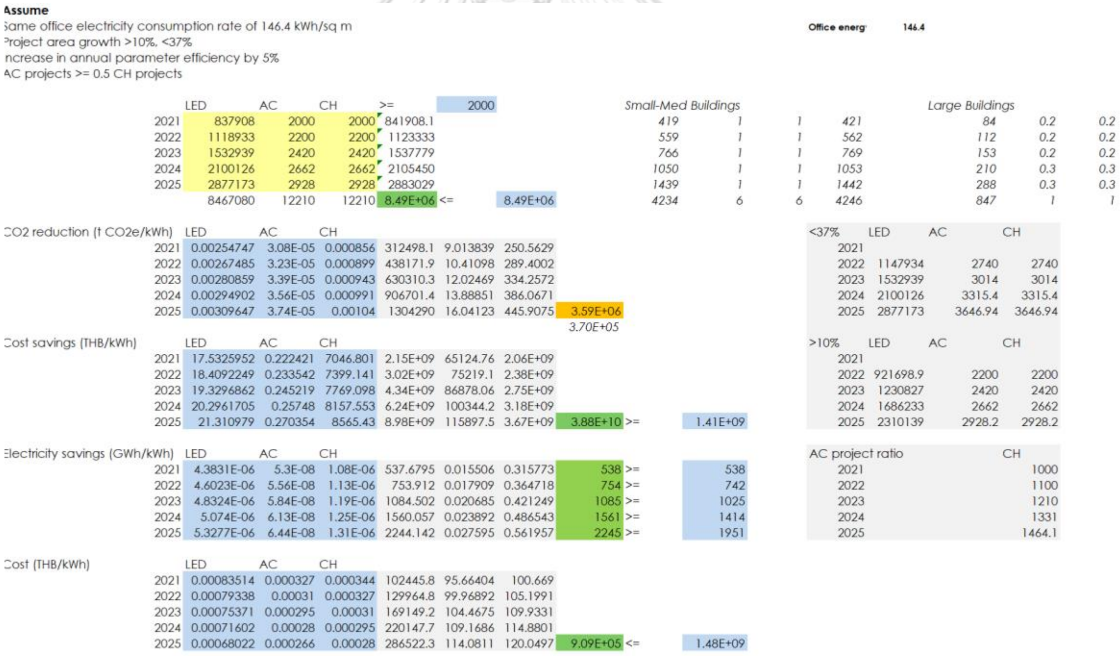
The colored comparisons reflect the values from Table 18, with green being most favorable and red being least favorable. Due to this conflict of objectives, two different model scenarios were implemented for different priorities that rank each objective as most important. Table 23 shows the two scenarios that the objectives were ranked by to compare the results for different goal programming orders.

Table 23: Optimization scenarios showing order of goal programming for different objective priorities

	Scenario 1 (Policy Maker)	**Scenario 1 (Building Management)**
Iteration 1	Maximize CO_2 emissions reduction	Maximize CO_2 emissions reduction
Iteration 2	Maximize electricity savings	Maximize cost savings
Iteration 3	Maximize cost savings	Maximize electricity savings

Both scenarios have 'Maximize CO_2 emissions reduction' as their top priority and therefore first iteration since the goal of this study is to meet the Thailand NDC target. Scenario 1 is shown for the perspective of a 'Policy Maker', which would prioritize electricity savings before cost savings. On the other hand, the 'Building Management' perspective of Scenario 2 would prioritize cost savings due to more budgetary constraints and business motives. The model outputs from these two scenarios were plotted on a 3D chart to compare the different outcomes and to identify potential trends or discrepancies.

Figure 17 shows an example goal programming model screenshot for the first iteration of Scenario 1. All the aforementioned input parameters from the 'project' MACC are included, as well as assumptions and constraints specified for the linear program.



Assume
Same office electricity consumption rate of 146.4 kWh/sq m
Project area growth >10%, <37%
ncrease in annual parameter efficiency by 5%
AC projects >= 0.5 CH projects

Office energ **146.4**

	LED	AC	CH	>=		2000	Small-Med Buildings				Large Buildings		
2021	837908	2000	2000	841908.1			*419*	*1*	*1*	*421*	*84*	*0.2*	*0.2*
2022	1118933	2200	2200	1123333			*559*	*1*	*1*	*562*	*112*	*0.2*	*0.2*
2023	1532939	2420	2420	1537779			*766*	*1*	*1*	*769*	*153*	*0.2*	*0.2*
2024	2100126	2662	2662	2105450			*1050*	*1*	*1*	*1053*	*210*	*0.3*	*0.3*
2025	2877173	2928	2928	2883029			*1439*	*1*	*1*	*1442*	*288*	*0.3*	*0.3*
	8467080	12210	12210	8.49E+06	<=	8.49E+06	*4234*	*6*	*6*	*4246*	*847*	*1*	*1*

CO2 reduction (t CO2e/kWh)	LED	AC	CH						
2021	0.00254747	3.08E-05	0.000856	312498.1	9.013839	250.5629			
2022	0.00267485	3.23E-05	0.000899	438171.9	10.41098	289.4002			
2023	0.00280859	3.39E-05	0.000943	630310.3	12.02469	334.2572			
2024	0.00294902	3.56E-05	0.000991	906701.4	13.88851	386.0671			
2025	0.00309647	3.74E-05	0.00104	1304290	16.04123	445.9075	3.59E+06		
							3.70E+05		

Cost savings (THB/kWh)	LED	AC	CH						
2021	17.5325952	0.222421	7046.801	2.15E+09	65124.76	2.06E+09			
2022	18.4092249	0.233542	7399.141	3.02E+09	75219.1	2.38E+09			
2023	19.3296862	0.245219	7769.098	4.34E+09	86878.06	2.75E+09			
2024	20.2961705	0.25748	8157.553	6.24E+09	100344.2	3.18E+09			
2025	21.310979	0.270354	8565.43	8.98E+09	115897.5	3.67E+09	3.88E+10	>=	1.41E+09

Electricity savings (GWh/kWh)	LED	AC	CH						
2021	4.3831E-06	5.3E-08	1.08E-06	537.6795	0.015506	0.315773	538	>=	538
2022	4.6023E-06	5.56E-08	1.13E-06	753.912	0.017909	0.364718	754	>=	742
2023	4.8324E-06	5.84E-08	1.19E-06	1084.502	0.020685	0.421249	1085	>=	1025
2024	5.074E-06	6.13E-08	1.25E-06	1560.057	0.023892	0.486543	1561	>=	1414
2025	5.3277E-06	6.44E-08	1.31E-06	2244.142	0.027595	0.561957	2245	>=	1951

Cost (THB/kWh)	LED	AC	CH						
2021	0.00083514	0.000327	0.000344	102445.8	95.66404	100.669			
2022	0.00079338	0.00031	0.000327	129964.8	99.96892	105.1991			
2023	0.00075371	0.000295	0.00031	169149.2	104.4675	109.9331			
2024	0.00071602	0.00028	0.000295	220147.7	109.1686	114.8801			
2025	0.00068022	0.000266	0.00028	286522.3	114.0811	120.0497	9.09E+05	<=	1.48E+09

<37%	LED	AC	CH
2021			
2022	1147934	2740	2740
2023	1532939	3014	3014
2024	2100126	3315.4	3315.4
2025	2877173	3646.94	3646.94

>10%	LED	AC	CH
2021			
2022	921698.9	2200	2200
2023	1230827	2420	2420
2024	1686233	2662	2662
2025	2310139	2928.2	2928.2

AC project ratio			CH
2021			1000
2022			1100
2023			1210
2024			1331
2025			1464.1

Figure 17: Excel screenshot of goal programming model Scenario 1, Iteration 1

The yellow area indicates the project area decision variables; the blue area indicates the constraints and corresponding parameter values for each EE project type; the grey area indicates the detailed output from the Simplex method computation; the green area indicates the main output from the Simplex method computation; the orange area indicates the main objective value for each iteration. In the iteration shown, the main objective value is the CO_2 emissions reduction. Refer to Appendix II for additional screenshots of the different iterations for Scenario 1.

4. Results and Discussion

4.1 General MACC results

Table 24 presents the NPV and MAC ranges of the ‘general’ MACC for the three different EE project types in an office VLB. Since our sample size for these findings is quite small, we are mainly interested in comparing the values on an individual basis rather than comparing them visually.

Table 24: Summary of NPV and MAC findings for general MACC curve (for all discount rates)

	NPV (THB)	***MAC (THB/tCO$_2$e)***
LED	(628,000) – (598,000)	64,000 – 66,000
AC	(1,258,000) – (1,169,000)	4,248,000 – 4,253,000
CH	(12,602,000) – (12,577,000)	56,401 – 61,000

Overall, the NPV values are highly negative and the MAC values are positive. This indicates that the projects are significantly lacking in cost effectiveness due to low financial return compared to their OPEX and CAPEX, which were the main costs accounted for in the study estimation.

As seen by the NPV ranges, the office CH project showed the most negative range while the LED project showed the least negative range. This indicates that for findings extrapolated from the EE and AA office buildings, an LED project would show more returns followed by an AC project. Reasons accounting for this include the fact that LED bulbs are relatively low cost and easy to reinstall despite their shorter life span. LED also has a lower electricity consumption rate than both AC and CH projects, resulting in a lower OPEX over time. Additionally, as shown in Section 3 the office AC project reported the lowest CAPEX, causing it to have a more favorable NPV over the CH project since both had the same OPEX values.

As for the MAC values in Table 24, the CH project is the most favorable despite its least favorable NPV standing. The favorable MAC for the CH project is reflected in its high value for CO_2 emissions reduction that was shown in Section 3.3, outweighing its high cost. The least favorable MAC value was for the AC project, which was higher than the CH project MAC range by over 75x. This is explained by the AC project's low CO_2 emissions reduction of 0.43 tCO_2e, drastically reducing its MAC.

These results are also reflected in the MACC curves themselves, with the one for a discount rate of 8% shown in Figure 18.

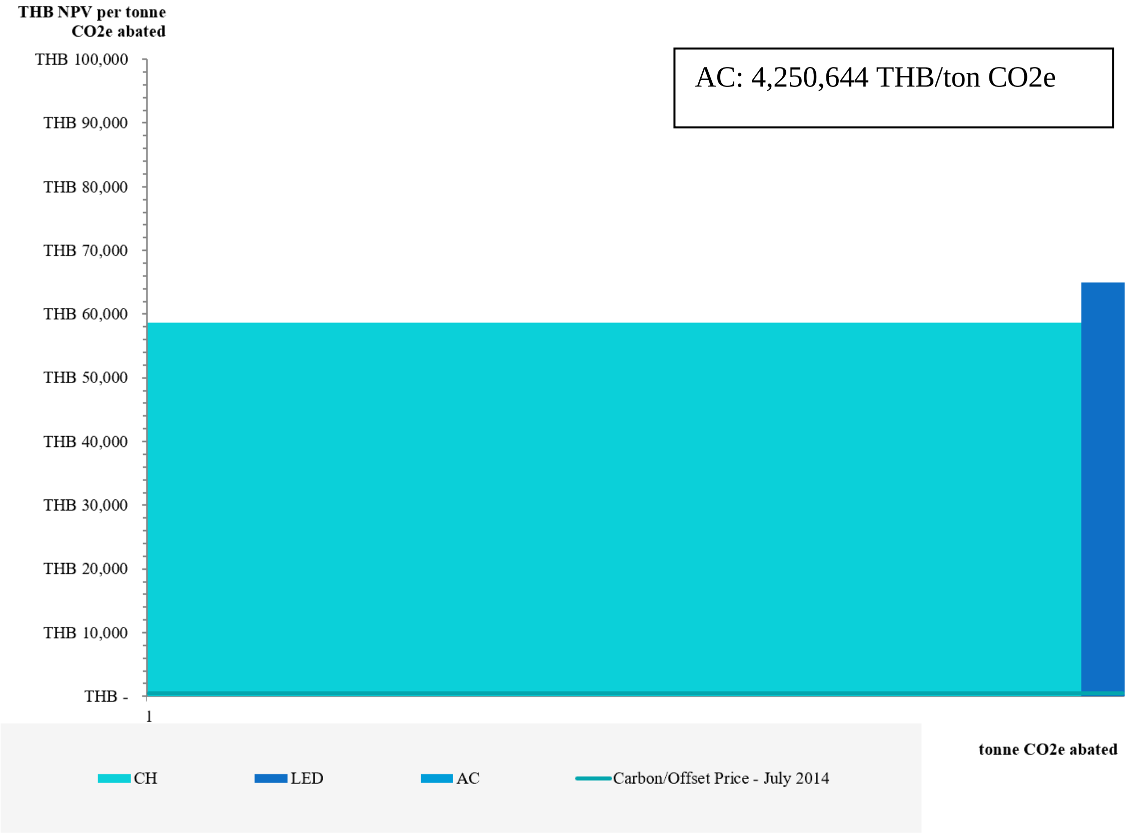


Figure 18: General MACC curve (discount rate = 8%)

Note: The AC project MAC value is shown in the text box.

As per the discussion, the CH project's favorable CO_2 emissions reduction is shown by its large width in the MACC curve. The AC project was not pictured on the scale provided since its MAC value was in the millions and significantly higher than the other EE projects. One more thing to note from the MACC curve is that all projects have MAC values well above the carbon price line of 429 THB, indicating that in all cases it would be more feasible to purchase carbon offsets rather than to pursue the projects. In the case of projects that have more accurate and minimized costs, this reference line may be in a different position.

Regarding trends between the discount rates, the CH project NPV value was most negative for a discount rate of 12% and least negative for a discount rate of 4%. In contrast, the AC and LED projects had the most negative NPV value for a discount rate of 4% and least negative for a discount rate of 12%. For MAC discount rate differences, again the CH project is different in that its MAC value is higher for a discount rate of 12% and lowest for a discount rate of 4% (converse to the AC and LED projects). In other words, the discount rate of 4% was most favorable for the CH project and the discount rate of 12% was most favorable for the AC and LED projects.

The MACC curves for the other discount rates of 4% and 12% rates are shown in Appendix II. Overall, these findings conclude that for the small sample size of PEECB office buildings the LED EE project type was the most favorable in terms of NPV and MAC.

4.2 Goal programming results

The goal programming results are shown below for Scenario 1 and Scenario 2. As previously stated, 3 Simplex linear model iterations were completed for each scenario since there were 3 objectives in total. The first iteration of both scenarios prioritized CO_2 emissions reduction, since that is the main objective of this study and fits in Thailand's best interests. Scenario 1 was completed for the perspective of a 'Policy Maker', with the second iteration prioritizing electricity savings before cost savings, while Scenario 2 was from the perspective of 'Building Management' and prioritized these objectives the opposite way.

Tables 25 and 26 show the decision variable, or project area, results from the goal programming optimization model for the three different objectives in office VLBs. Note that these values are not per consumption but are reported in their actual units, since we are interested in comparing them to the EPPO targets that Thailand set in the EEDP.

Table 25: Goal programming model output for office LCB project area to be completed for each EE method in 2021-2025 (Scenario 1)

Area (sq m)	***2021***	***2022***	***2023***	***2024***	***2025***	***Total Area***
LED	769,345	1,054,003	1,443,984	1,978,258	2,710214	**7,955,805**
AC	17,268	23,657	32,410	44,401	60,830	**178,565**
CH	34,535	47,313	64,819	88,802	121,659	**357,130**

Table 26: Goal programming model output for office LCB project area to be completed for each EE method in 2021-2025 (Scenario 2)

Area (sq m)	***2021***	***2022***	***2023***	***2024***	***2025***	***Total Area***
LED	763,652	1,046,203	1,433,298	1,963,619	2,690,158	**7,896,930**
AC	32,463	35,709	39,280	43,208	47,529	**198,190**
CH	64,926	71,419	78,560	86,417	95,058	**396,380**

The main difference between Scenario 1 and Scenario 2 is that the second and third objectives are in different orders; for the former electricity savings is prioritized as the second objective after maximizing CO_2 emissions reduction whereas for the latter cost savings is prioritized. The total project areas designated to each EE project type add up to the total area available of 8,491,500 sq m. When looking at the total optimized project area for each EE project type, it is evident that there isn't much difference between Scenario 1 and Scenario 2. Due to the constraints set on the linear model, the project area increases by at least 10% and up to 37% every year. Moreover, the project area for AC projects is at least half of CH projects since EE changes are made in a 1:2 ratio on HVAC units in general.

In both scenarios, the goal programming model recommends the highest project area to be allocated to LED projects in office LCBs. In Section 3.3, this was also reflected in the 'general' MACC results due to the high CO_2 emissions reduction potential of LED projects (2.6×10^{-3} tCO_2e/kWh) as compared to the other types of projects, as well as its more favorable electricity savings of 4.4×10^{-6} GWh/kWh. The CH project had the most favorable cost savings parameter of 7.1×10^{3} THB/kWh and had the 2nd most recommended proportion of project area per year after the LED project. From this, it can be said that despite LED seeming favorable in many project metrics and being designated as the highest EE project area, the CH and AC projects are also essential to reach the EEDP cost savings and budget constraints.

To further illustrate the conclusions from the goal programming model and to compare its outputs with Thailand's national targets, Tables 27 and 28 show the same outputs for Scenario 1 and Scenario 2. The outputs in these tables are given in terms of the objectives of the model: CO_2 emissions reduction, electricity savings, and cost savings.

Table 27: Goal programming model output for project parameters from EE methods completed in 2021-2025 (Scenario 1)

	CO_2 emissions reduction (tCO_2e)	***Electricity Savings (kWh)***	***Cost savings (THB)***
LED	$3\text{x}10^6$	$6\text{x}10^3$	$2\text{x}10^{10}$
AC	$9\text{x}10^2$	2	$7\text{x}10^6$
CH	$5\text{x}10^4$	$6\text{x}10^1$	$4\text{x}10^{11}$
Total	**$3\text{x}10^6$**	**$6\text{x}10^3$**	**$4\text{x}10^{11}$**
% of target	**8X**	**1.1X**	**286X**

Table 28: Goal programming model output for project parameters from EE methods completed in 2021-2025 (Scenario 2)

	CO_2 emissions reduction (tCO_2e)	***Electricity Savings (kWh)***	***Cost savings (THB)***
LED	$3\text{x}10^6$	$6\text{x}10^3$	$2\text{x}10^{10}$
AC	$10\text{x}10^2$	2	$7\text{x}10^6$
CH	$6\text{x}10^4$	$7\text{x}10^1$	$5\text{x}10^{11}$
Total	**$3\text{x}10^6$**	**$6\text{x}10^3$**	**$5\text{x}10^{11}$**
% of target	**8X**	**1.1X**	**357X**

As stated previously, the results between Scenario 1 and Scenario 2 are very similar when combining the parameter results from all years in the range 2021-2025. The main difference is in the percentage of EEDP target achieved: the total cost savings value for Scenario 1 was equal to 286x of the national target whereas the value for Scenario 2 was equal to 357x. This is in line with the prioritization of the objectives for each scenario since Scenario 2 placed more emphasis on achieving cost savings. It is also necessary to note that despite this increase in cost savings potential, there was little tradeoff in terms of CO_2 emissions reduction or electricity savings, both of which remained the same in comparison to the target (8x and 1.1x, respectively).

In comparison to their respective PDP targets, the CO_2 reduction, electricity savings, and cost savings results are significant. These targets were set by an assumption of 37% of the total EPPO target for LCBs in accordance with the office building share of electricity consumption. The CO_2 reduction total of $3x10^6$ tCO_2e is 8x of its $3.7x10^5$ tCO_2e target, whereas the totals for electricity and cost savings also exceed their targets of $2.7x10^{10}$ kWh and $1.4x10^9$ THB, respectively.

In addition to comparison with the EEDP targets, it is also necessary to compare the CO_2 emissions reduction results with Thailand's NDC target of 555 million (or $555x10^6$) tCO_2e. The total 5-year CO_2 emissions reduction value of $3x10^6$ tCO_2e from both scenarios is equal to 0.54% of the NDC target to be achieved by 2030. This value accounts for a five (rather than 10) year period and consists of EE projects in just office buildings of LCBs, explaining why the proportion of the total goal is quite small. Other building types, project initiatives, and sectors (most notably the industrial sector) are likely to contribute to achieving the NDC target as well.

To give a better understanding of what this project implementation would look like in reality, Table 29 shows the goal programming output area in terms of the number of LBs and VLBs that would undergo modifications or additions for each project parameter.

Table 29: Goal programming model output for number of large (LB) and very large (VLB) buildings required to achieve results

	CO_2 emissions reduction (tCO_2e)	**Electricity Savings (kWh)**	**Cost savings (THB)**
VLB	800	20	40
LB	3,900	90	200

When comparing the project areas for each building type in terms of size, we use the simplified comparisons of 2,000 sq m for LBs 10,000 sq m for VLBs. Although this is not inclusive of all building types, it gives a preliminary idea of the scale required to implement these EE projects to meet Thailand's targets.

As shown above, there would need to be a significantly higher number of buildings with EE project implementation to reach the CO_2 emissions reduction value from the goal programming output. 800 VLBs (or 3,900 LBs) would require project work, which is unlikely to occur due to the limited number of office buildings available in the BMR and the degree of effort and coordination that would be required to implement projects in 40 VLBs (or 780 LBs) every year in 2021-2025. Furthermore, approximately 160 buildings per year would be required to undergo LED projects, which on a minor scale is likely but on a large nationwide scale is less realistic.

As for electricity savings and cost savings, the required number of buildings is more realistic when broken down by year. It can be concluded that since the goal programming output far exceeds the EEDP targets, it is not necessary to fully implement its recommendations to achieve the results necessary.

To compare the results of the goal programming model visually, Figures 19 and 20 show the iteration results for Scenario 1 and Scenario 2 and the corresponding values of the objectives.

The CO_2 emissions reduction and electricity savings results are on the left axis, while the cost savings results are on the right axis.

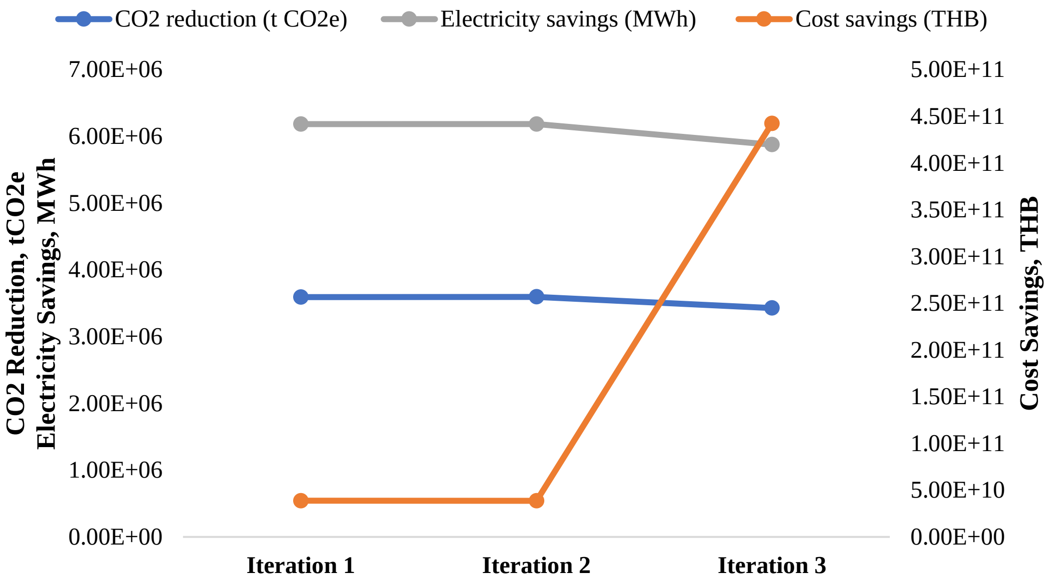


Figure 19: Goal programming model graphical output for project parameters from EE methods completed in 2021-2025 (Scenario 1)

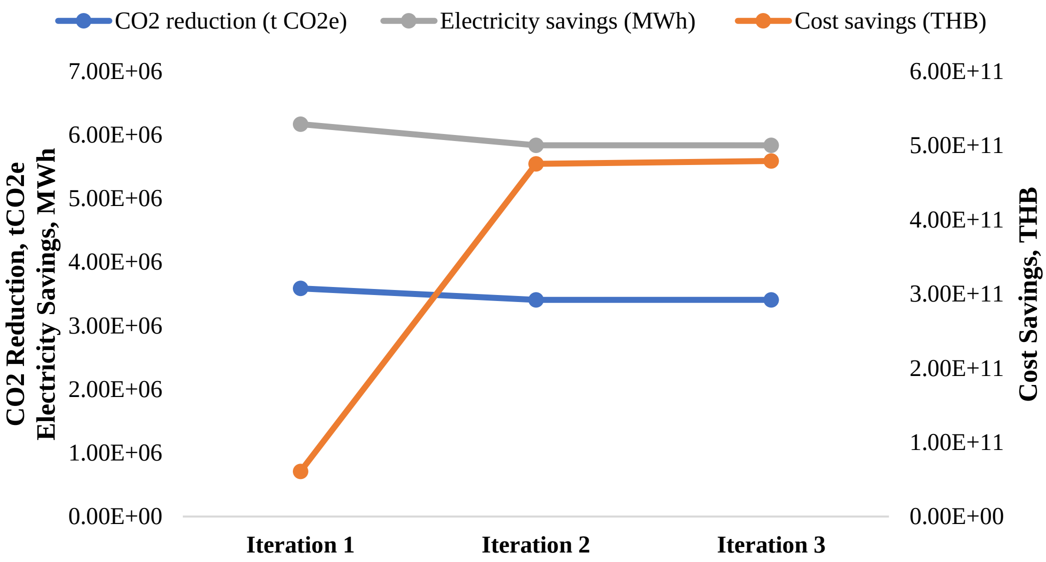


Figure 20: Goal programming model graphical output for project parameters from EE methods completed in 2021-2025 (Scenario 2)

In both figures, the CO_2 emissions reduction value does not significantly change over the iterations in both Scenario 1 and Scenario 2. Between Iterations 1 and 3 for both scenarios, the value decreases 6% in total from $3.6x10^6$ tCO_2e to $3.4x10^6$ tCO_2e, abiding by the degradation constraint set in the preemptive goal programming.

Likewise, the electricity savings value also does not change significantly from its Iteration 1 value in both scenarios. The value decreases by 2-3% from its first optimized value of $6x10^6$ MWh. The lower percentage is attributed to Scenario 1, in which the electricity savings objective took priority over the cost savings objective. These results support the fact that LED projects are most favorable in the case of CO_2 emissions reduction and electricity savings, since the optimized project areas favor LED project implementation and result in a high value for both parameters.

When examining how the cost savings value changes over the iterations for each scenario, there is a larger increase overall for Scenario 1 from $4x10^{10}$ THB to $4x10^{11}$ THB, while for Scenario 2 the final value is higher from 6x10^{10} THB to 5x10^{11} THB. The higher value in Scenario 2 can be accounted for by the higher prioritization of the cost savings objective in Iteration 2.

To compare the goal programming results further visually, Figure 21 shows a 3D plot of the iteration values for each objective.

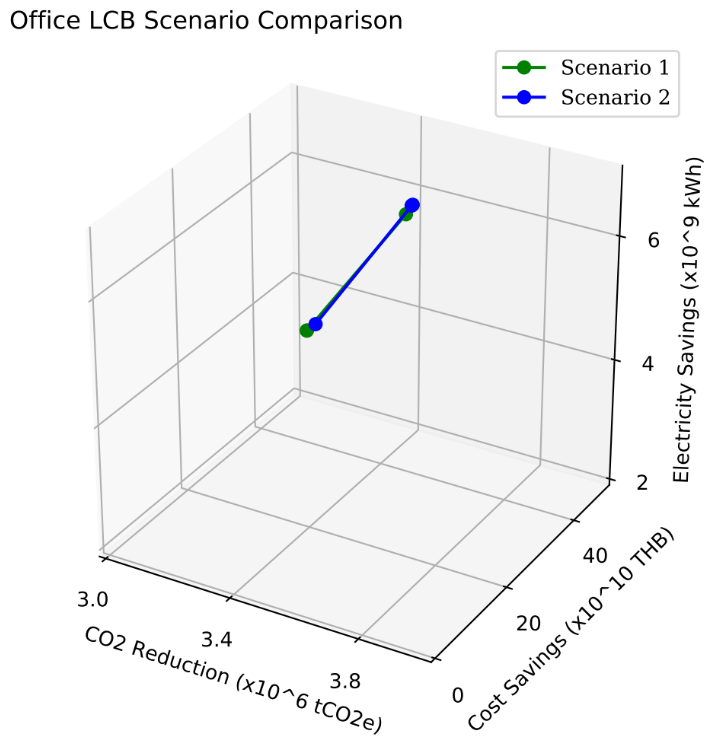


Figure 21: 3D plot of goal programming model output for Scenario 1 and 2

When viewed on a 3D plot, it is much clearer to see that the model outputs are inverted due to the different ordering in goal programming priorities. Depending on the stakeholder involved in the project, the final result (at the points toward the right of the graph) is still quite similar save for some differences in the final cost saving value achieved.

From the goal programming model, all objectives were exceeded by at least 1x, indicating that the EE implementation in office LCBs was a success in reaching the Thailand NDC and EEDP targets.

5. Conclusion and Further Study

5.1 Summary of findings

This study began with the main objective of finding a framework and modeling tool to aid Thailand in meeting its 2030 NDC target of reducing CO_2 emissions by 555 million tCO_2e. With further research, it was found that CO_2 emissions reduction could not be the sole focus due to other targets that the EEDP has, which had conflicting objectives with carbon emissions. Therefore, in the final goal programming analysis the other targets of electricity savings and cost savings were also included.

Therefore, the findings of this study consisted of analyzing outcomes for CO_2 emissions reduction, electricity savings, and cost savings for EE projects in Bangkok's LCBs for the period of 2021-2025. As stated before, there were two phases to the study to achieve the main objective. Phase 1 began with an analysis to quantify the measurable benefits stated above (CO_2 emissions reduction, electricity savings, and cost savings) of EE projects in Bangkok LCBs. The MACC was the main analysis tool used as part of this phase, consisting of a PEECB 'project' MACC and a 'general' MACC curve. In addition to the three main measures of interest, the MACC data revealed other insights such as project expenditure over time and total EE project area required for different types of technologies and LCBs.

From the PEECB 'project' MACC curve, there was no discernible trend regarding the type of LCB when comparing offices, retail centers, hospitals, and hotels. What made more difference was the EE project type that was employed in each building and likely the buildings' individual characteristics that affected their energy load profile and consumption.

Regarding comparisons between the EE project types, it was shown that CO_2 emissions reduction was most favorable for the CH projects and lowest for the AC projects regardless of building type. This was evident in the greater range in the x-axis exhibited in the visual MACC curves, as well as the higher quantity of CO_2 emissions reduction reported for chiller installation and optimization projects. When comparing cost effectiveness between the projects, however, the

CH projects were shown to be the least cost effective and had the highest MAC value when excluding project OPEX. When including project OPEX, they became the most cost effective likely due to the relatively lower operating costs reported for CH-related LCBs.

The 'project' MACC findings are valid for the scope of the PEECB project buildings themselves and not necessarily all LCBs in the BMR, since each project site was unique in its energy requirements, costs, and results. To rectify this, the 'general' MACC was created to use the office building PEECB CO_2 emissions reduction, electricity savings, and CAPEX data on a per area basis. The MACC inputs were then created for a VLB of 10,000 sq m to simulate similar conditions in project area to study each EE project type.

Among all EE project types in the 'general' MACC, AC installations were shown to be the least cost-effective EE method for CO_2 emissions reduction. On the other hand, CH installations offer the most well-rounded solution for both cost savings and emissions reduction. Overall, the LED project showed the most attractive NPV indicating that the project utilizes capital better to reduce emissions. This return can be attributed to the low-rated LED bulb life (2.9 years) compared to the average life span of an HVAC unit (15-20 years).

As discussed, each EE project type had conflicts and tradeoffs in each of the optimization input parameters. The standardized LED office project had the highest CO_2 emissions reduction range and the highest electricity savings, while the CH project had the most favorable cost savings. The AC project had the most attractive total cost, which was the lowest of the three EE project types. Ultimately for office buildings, LED installations provide the most efficient returns on electricity savings, cost savings, and MAC.

Next, as part of Phase 2, the characteristics for office buildings from the 'general' MACC curve were used as inputs to the goal programming model using the Simplex method. Two scenarios were studied based on the perspective of a 'Policy Maker' and that of 'Building Management', which prioritized the objectives of maximizing CO_2 emissions reduction, electricity savings, and cost savings differently. The objectives were met by the model with two optimized five-year EE project plans for each scenario. These project plans consisted of the ideal estimated project area to implement for each EE project type (LED, AC, CH) in office LCBs.

When inputting the conflicting parameters from the MACC curve into the goal programming model, the LED project results in the highest recommended project area year-on-year for the period 2021-2025. This is likely due to its favorable CO_2 emissions reduction over the other two project types and the fact that this was the highest priority objective in the goal programming.

The CH and AC projects also have designated, albeit less, project areas due to their cost savings and budgetary outlooks. Overall, from the project planning outputted by the model, each of the objective values far exceed the EEDP target and meet the office LCB requirement for Thailand's NDC target as well.

It was shown that all EE project types are needed to build a cohesive plan to meet Thailand's NDC and EEDP targets. Based on the optimized solution to meet the three objectives in EE project planning, CO_2 emissions in office buildings could be mitigated by approximately 8x of the EEDP target in the next five years, followed by 1.1x for electricity savings and >200x for cost savings. As offices are a LCB building type that consumes over a third of the total electricity generation in Thailand, it is evident that this can contribute a significant positive impact in helping meet EPPO's goals and providing a benchmark for private sector companies and other industries to aim for.

5.2 Research limitations

These research results should not be considered definitive but instead as a starting point for further analysis of CO_2 emissions reduction potential in the BMR commercial building sector and for different sectors within Thailand. The current study aimed to analyze and simulate the findings from a publicly available data source and set the framework and modeling analysis to extend to larger data sets as well.

Due to limited publicly available information, the study lent itself to a few limitations:

First, further refinement of the ‘project’ and ‘general’ MACC curves may be needed by modifying assumptions and revising CO_2 emissions reduction potentials based on the adoption rate. It is rare that a project’s expected benefit will be equal to its actual results, and the parameters that were analyzed as part of this study are no exception (CO_2 emissions reduction, electricity savings, cost savings). Therefore, assumptions to increase the range of uncertainty of these parameters can be put in place to account for scenarios where, for instance, a building may not use all its lighting available, or the AC optimization of a particular project is incorrectly implemented and produces lower cost savings than initially estimated.

Second, the MACC does not account for building characteristics such as age or height, which is likely to affect the cost values of project CAPEX and annual facilities OPEX since older facilities will require more maintenance and general upkeep. If more advanced building simulations or data was available, this could be accounted for as part of the MACC input parameters or goal programming constraints. This factor will be important to consider for stakeholders managing projects in buildings with unique features or newer designs that do not have historical data to account for.

Third, the method to estimate OPEX based on annual electricity consumption may be too simple and requires a more in-depth analysis to account for life cycle costs accurately. The OPEX of a building is not likely to remain static over time, therefore factors such as economies of scale or increased efficiencies should be considered to accurately reflect the lifetime cost of a project. On the other hand, OPEX may increase unexpectedly over time due to unforeseen circumstances or extra costs that were not taken into consideration when first estimating the costs. For example, the cooling medium used for newer HVAC models may be more costly per unit volume compared to older models, which can contribute to increased total costs.

Fourth, the goal programming model also has limitations, in that the user must specify constraints to ensure the results are realistic and achievable. The model was programmed to have increasing project efficiencies by at least 5% per year, which in actuality could show a more negative trend if the equipment installed does not function properly or maintenance needs to be done often. To reflect a more realistic scenario, it may be more plausible to lower this growth rate to account for project uncertainties and limitations.

5.3 Opportunities for further study

For further accuracy and relevance using the MACC curve, the tool should ideally account for more recent data from publicly available EE projects, since the parameters used in this study were based on a 2014 study. More recent data would support the robustness of the goal programming model as well, allowing a more realistic planning scenario to maximize CO_2 emissions reduction over the next five years or longer.

Additionally, dynamic MACC calculations and life cycle costs can be developed and compared with the static MACC from the study to identify potential errors in the assumptions used and gain a more accurate understanding of how the project costs and emissions will evolve over time. This links back to the study limitation of not accounting for dynamic changes in parameters over time, since increases or decreases in efficiencies and cost can significantly alter project outcomes.

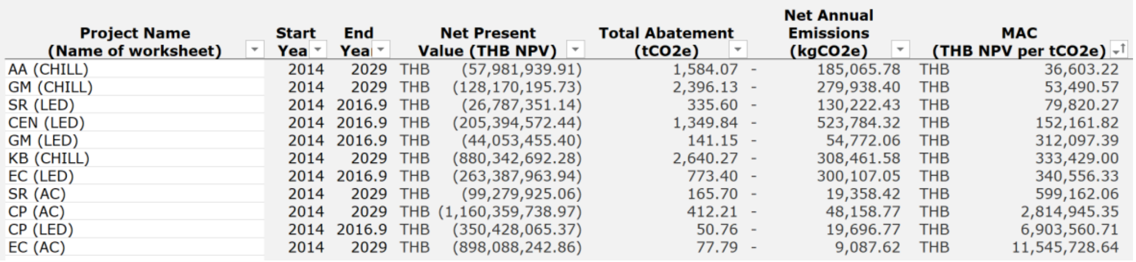
In the case of the optimization for project planning, the goal programming model can be extended to other types of LCB including hotels, hospitals, and retail centers. More EE project types can also be compared and optimized for project planning to accurately reflect all the methods that are available to be used in buildings.

The tools used in this study can also be adapted for evaluating projects of interest in other sectors such as alternative energy or the industrial sector. Input parameters of CO_2 emissions reduction, electricity savings, and cost savings for these sectors would likely be different than those in the commercial sector, helping to extend the findings from the study to cover more stakeholders in Thailand. Combined with more recent parameters, the findings would result in a more definitive and broad scope of EE project planning for multiple buildings and sectors in the country. The project areas recommended to employ in each year would be larger than the preliminary values of this study and would vary not only by the type of building but by the nature of its use as well.

This study has suggested that it is entirely possible to achieve Thailand’s EEDP and NDC targets within its budget. In addition to its plans to curb CO_2 emissions, there is potential for applications of the same EE methods to achieve additional savings in other areas and other sectors. The next step this study recommends is to begin applying more standardized tools and processes to coordinate EE project implementation in the commercial sector, which will allow the reduction of overall costs in Bangkok’s buildings and a lowering of its climate change impact in the Asia Pacific region.

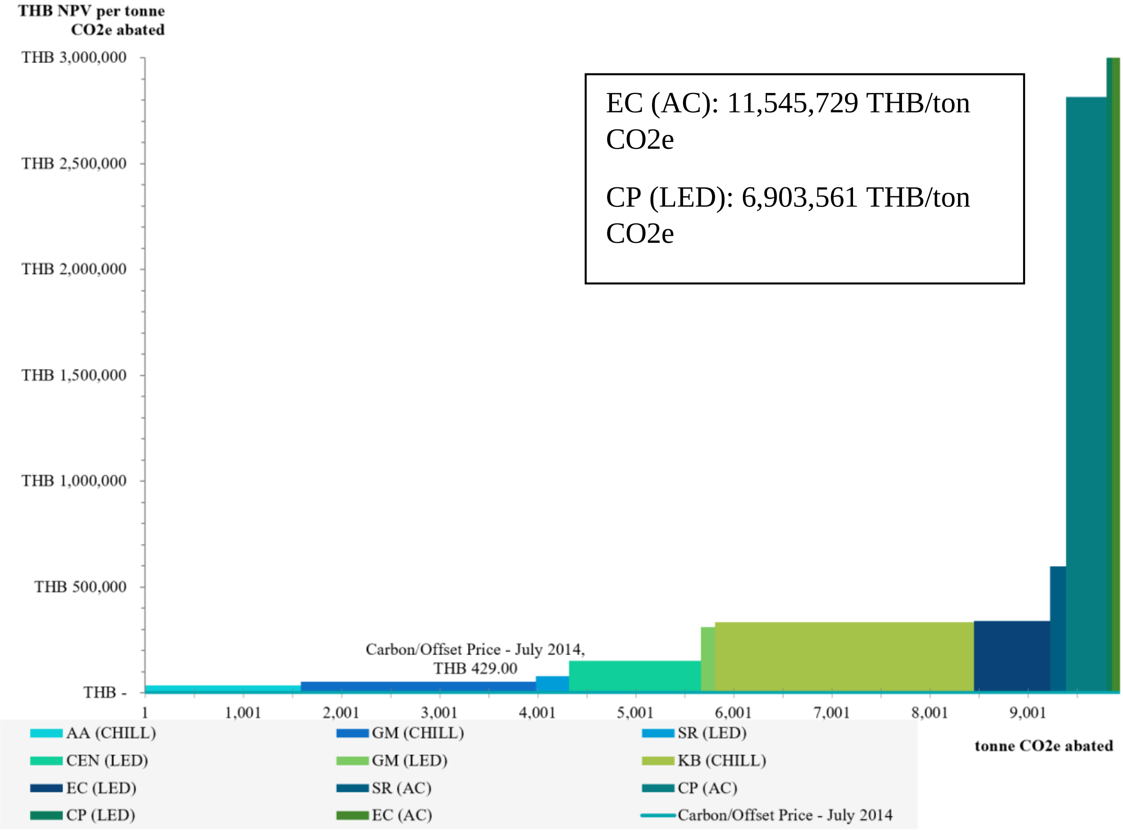
Appendices

Appendix I: MACC Inputs and Results



Project Name (Name of worksheet)	Start Yea	End Yea		Net Present Value (THB NPV)	Total Abatement (tCO2e)		Net Annual Emissions (kgCO2e)		MAC (THB NPV per tCO2e)
AA (CHILL)	2014	2029	THB	(57,981,939.91)	1,584.07	-	185,065.78	THB	36,603.22
GM (CHILL)	2014	2029	THB	(128,170,195.73)	2,396.13	-	279,938.40	THB	53,490.57
SR (LED)	2014	2016.9	THB	(26,787,351.14)	335.60	-	130,222.43	THB	79,820.27
CEN (LED)	2014	2016.9	THB	(205,394,572.44)	1,349.84	-	523,784.32	THB	152,161.82
GM (LED)	2014	2016.9	THB	(44,053,455.40)	141.15	-	54,772.06	THB	312,097.39
KB (CHILL)	2014	2029	THB	(880,342,692.28)	2,640.27	-	308,461.58	THB	333,429.00
EC (LED)	2014	2016.9	THB	(263,387,963.94)	773.40	-	300,107.05	THB	340,556.33
SR (AC)	2014	2029	THB	(99,279,925.06)	165.70	-	19,358.42	THB	599,162.06
CP (AC)	2014	2029	THB	(1,160,359,738.97)	412.21	-	48,158.77	THB	2,814,945.35
CP (LED)	2014	2016.9	THB	(350,428,065.37)	50.76	-	19,696.77	THB	6,903,560.71
EC (AC)	2014	2029	THB	(898,088,242.86)	77.79	-	9,087.62	THB	11,545,728.64

Figure 22: PEECB project MACC results (discount rate = 8%, including OPEX)

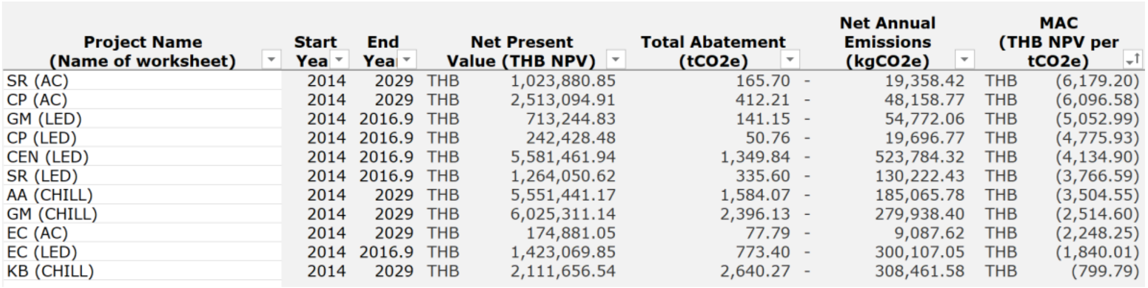


EC (AC): 11,545,729 THB/ton CO2e

CP (LED): 6,903,561 THB/ton CO2e

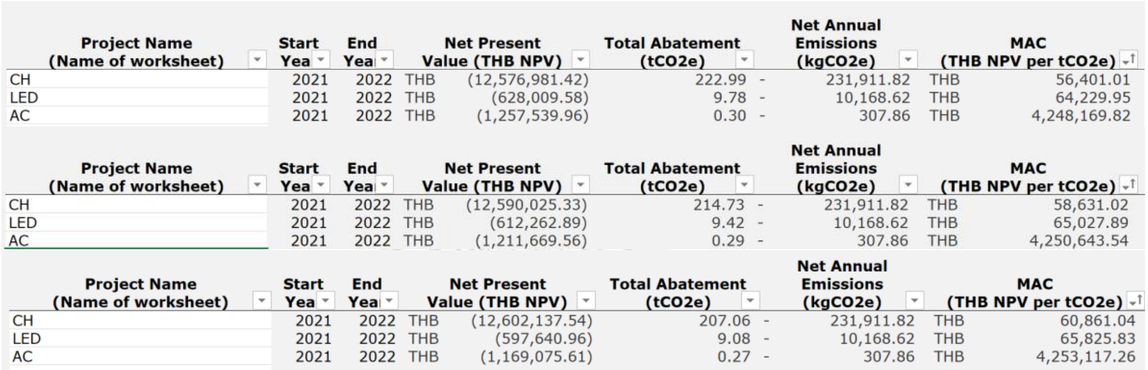
Figure 23: PEECB project MACC curve (discount rate = 8%, including OPEX)

Note: The EC and CP AC and LED projects had very large MAC values and could not be accurately shown on the graph. Their MAC values are shown in the text box.



Project Name (Name of worksheet)	Start Yea	End Yea		Net Present Value (THB NPV)	Total Abatement (tCO2e)		Net Annual Emissions (kgCO2e)		MAC (THB NPV per tCO2e)
SR (AC)	2014	2029	THB	1,023,880.85	165.70	-	19,358.42	THB	(6,179.20)
CP (AC)	2014	2029	THB	2,513,094.91	412.21	-	48,158.77	THB	(6,096.58)
GM (LED)	2014	2016.9	THB	713,244.83	141.15	-	54,772.06	THB	(5,052.99)
CP (LED)	2014	2016.9	THB	242,428.48	50.76	-	19,696.77	THB	(4,775.93)
CEN (LED)	2014	2016.9	THB	5,581,461.94	1,349.84	-	523,784.32	THB	(4,134.90)
SR (LED)	2014	2016.9	THB	1,264,050.62	335.60	-	130,222.43	THB	(3,766.59)
AA (CHILL)	2014	2029	THB	5,551,441.17	1,584.07	-	185,065.78	THB	(3,504.55)
GM (CHILL)	2014	2029	THB	6,025,311.14	2,396.13	-	279,938.40	THB	(2,514.60)
EC (AC)	2014	2029	THB	174,881.05	77.79	-	9,087.62	THB	(2,248.25)
EC (LED)	2014	2016.9	THB	1,423,069.85	773.40	-	300,107.05	THB	(1,840.01)
KB (CHILL)	2014	2029	THB	2,111,656.54	2,640.27	-	308,461.58	THB	(799.79)

Figure 24: PEECB project MACC results (discount rate = 8%, no OPEX)



Project Name (Name of worksheet)	Start Yea	End Yea		Net Present Value (THB NPV)	Total Abatement (tCO2e)		Net Annual Emissions (kgCO2e)		MAC (THB NPV per tCO2e)
CH	2021	2022	THB	(12,576,981.42)	222.99	-	231,911.82	THB	56,401.01
LED	2021	2022	THB	(628,009.58)	9.78	-	10,168.62	THB	64,229.95
AC	2021	2022	THB	(1,257,539.96)	0.30	-	307.86	THB	4,248,169.82

Project Name (Name of worksheet)	Start Yea	End Yea		Net Present Value (THB NPV)	Total Abatement (tCO2e)		Net Annual Emissions (kgCO2e)		MAC (THB NPV per tCO2e)
CH	2021	2022	THB	(12,590,025.33)	214.73	-	231,911.82	THB	58,631.02
LED	2021	2022	THB	(612,262.89)	9.42	-	10,168.62	THB	65,027.89
AC	2021	2022	THB	(1,211,669.56)	0.29	-	307.86	THB	4,250,643.54

Project Name (Name of worksheet)	Start Yea	End Yea		Net Present Value (THB NPV)	Total Abatement (tCO2e)		Net Annual Emissions (kgCO2e)		MAC (THB NPV per tCO2e)
CH	2021	2022	THB	(12,602,137.54)	207.06	-	231,911.82	THB	60,861.04
LED	2021	2022	THB	(597,640.96)	9.08	-	10,168.62	THB	65,825.83
AC	2021	2022	THB	(1,169,075.61)	0.27	-	307.86	THB	4,253,117.26

Figure 25: General MACC results (in order of discount rate = 4%, 8%, 12%)

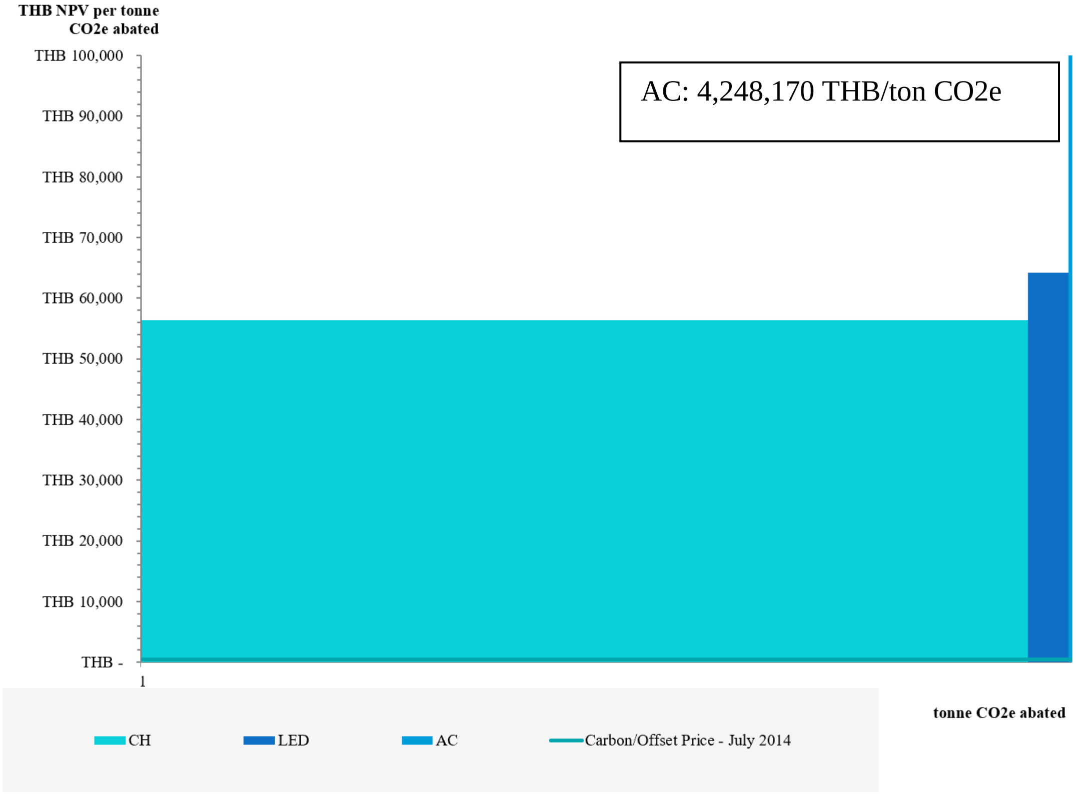


Figure 26: General MACC curve (discount rate = 4%)

Note: The AC project MAC value is shown in the text box.

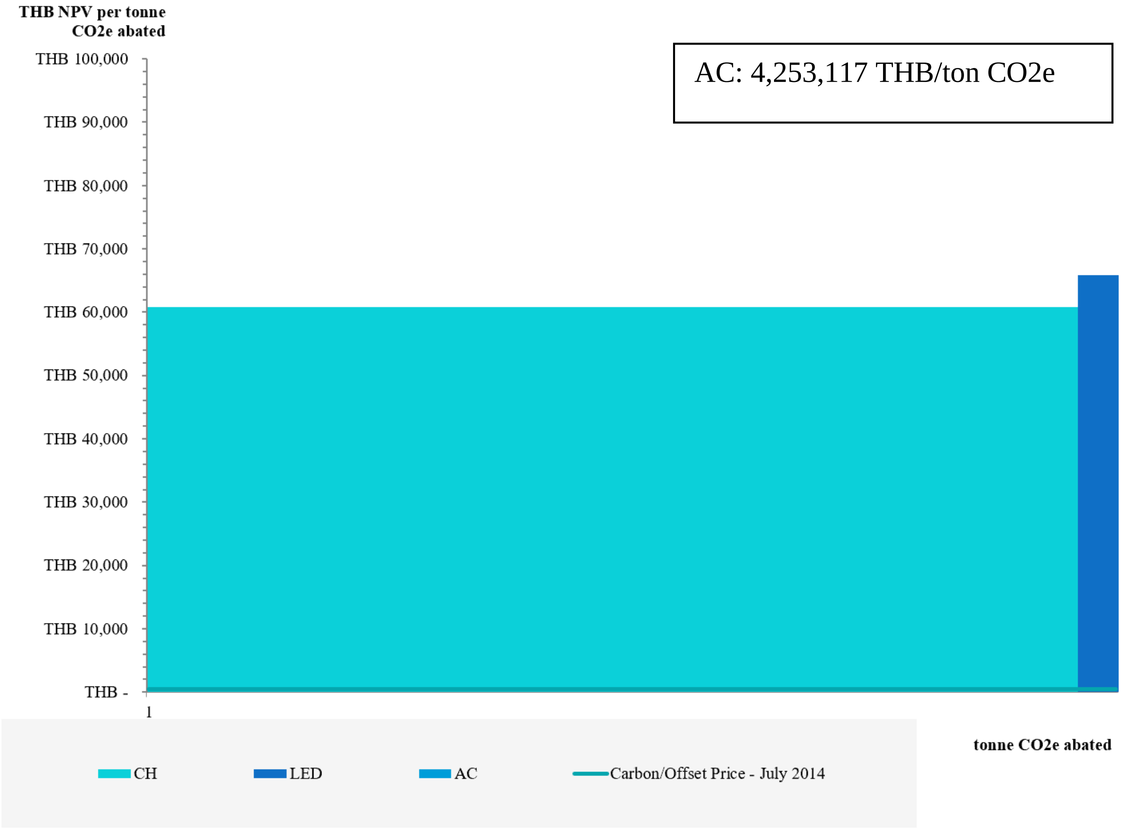
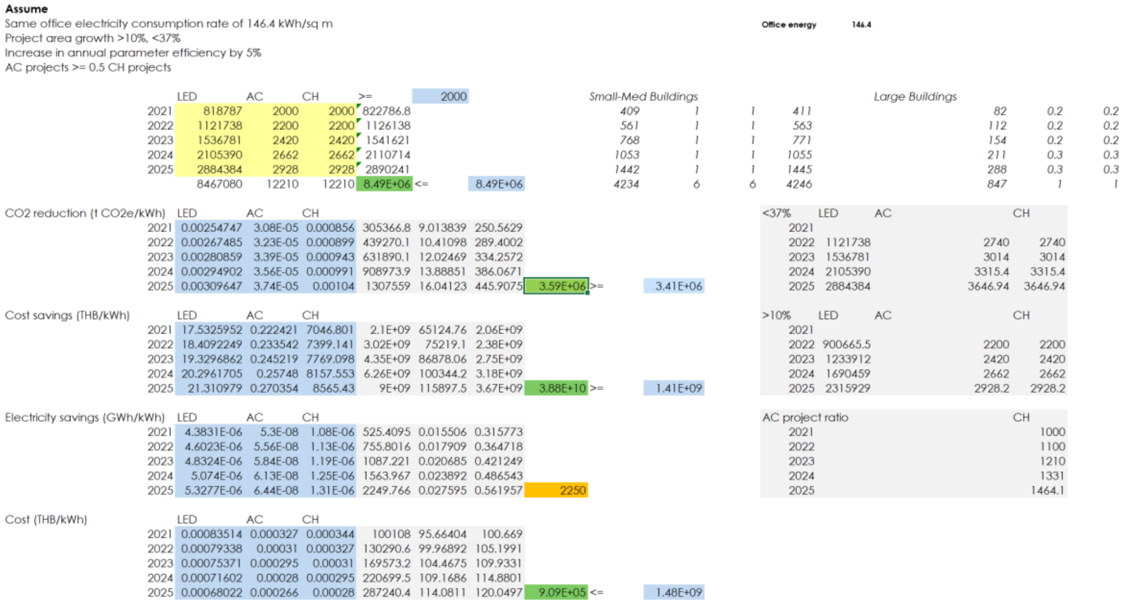


Figure 27: General MACC curve (discount rate = 12%)

Note: The AC project MAC value is shown in the text box.

Appendix II: Goal Programming Model Inputs and Results



Assume
Same office electricity consumption rate of 146.4 kWh/sq m
Project area growth >10%, <37%
Increase in annual parameter efficiency by 5%
AC projects >= 0.5 CH projects

Office energy **146.4**

	LED	AC	CH	>=	2000	
2021	818787	2000	2000	822786.8		
2022	1121738	2200	2200	1126138		
2023	1536781	2420	2420	1541621		
2024	2105390	2662	2662	2110714		
2025	2884384	2928	2928	2890241		
	8467080	12210	12210	8.49E+06	<=	8.49E+06

Small-Med Buildings			
409	1	1	411
561	1	1	563
768	1	1	771
1053	1	1	1055
1442	1	1	1445
4234	6	6	4246

Large Buildings		
82	0.2	0.2
112	0.2	0.2
154	0.2	0.2
211	0.3	0.3
288	0.3	0.3
847	1	1

CO2 reduction (t CO2e/kWh)	LED	AC	CH						
2021	0.00254747	3.08E-05	0.000856	305366.8	9.013839	250.5629			
2022	0.00267485	3.23E-05	0.000899	439270.1	10.41098	289.4002			
2023	0.00280859	3.39E-05	0.000943	631890.1	12.02469	334.2572			
2024	0.00294902	3.56E-05	0.000991	908973.9	13.88851	386.0671			
2025	0.00309647	3.74E-05	0.00104	1307559	16.04123	445.9075	3.59E+06	>=	3.41E+06

Cost savings (THB/kWh)	LED	AC	CH						
2021	17.5325952	0.222421	7046.801	2.1E+09	65124.76	2.06E+09			
2022	18.4092249	0.233542	7399.141	3.02E+09	75219.1	2.38E+09			
2023	19.3296862	0.245219	7769.098	4.35E+09	86878.06	2.75E+09			
2024	20.2961705	0.25748	8157.553	6.26E+09	100344.2	3.18E+09			
2025	21.310979	0.270354	8565.43	9E+09	115897.5	3.67E+09	3.88E+10	>=	1.41E+09

Electricity savings (GWh/kWh)	LED	AC	CH				
2021	4.3831E-06	5.3E-08	1.08E-06	525.4095	0.015506	0.315773	
2022	4.6023E-06	5.56E-08	1.13E-06	755.8016	0.017909	0.364718	
2023	4.8324E-06	5.84E-08	1.19E-06	1087.221	0.020685	0.421249	
2024	5.074E-06	6.13E-08	1.25E-06	1563.967	0.023892	0.486543	
2025	5.3277E-06	6.44E-08	1.31E-06	2249.766	0.027595	0.561957	2250

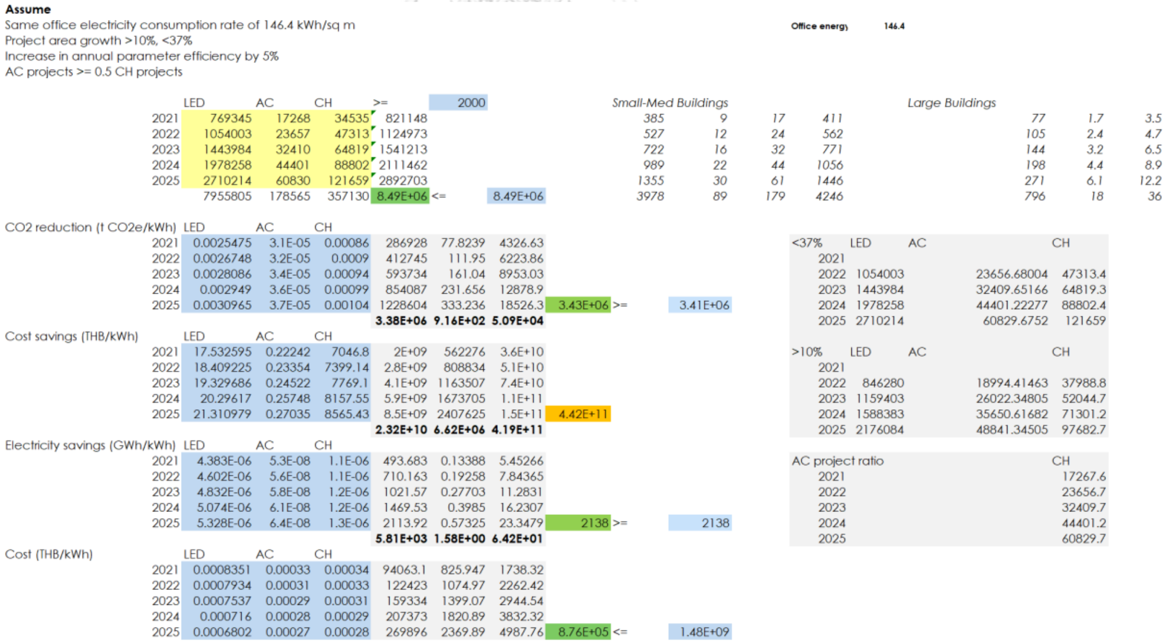
Cost (THB/kWh)	LED	AC	CH						
2021	0.00083514	0.000327	0.000344	100108	95.66404	100.669			
2022	0.00079338	0.00031	0.000327	130290.6	99.96892	105.1991			
2023	0.00075371	0.000295	0.00031	169573.2	104.4675	109.9331			
2024	0.00071602	0.00028	0.000295	220699.5	109.1686	114.8801			
2025	0.00068022	0.000266	0.00028	287240.4	114.0811	120.0497	9.09E+05	<=	1.48E+09

<37%	LED	AC		CH
2021				
2022	1121738		2740	2740
2023	1536781		3014	3014
2024	2105390		3315.4	3315.4
2025	2884384		3646.94	3646.94

>10%	LED	AC		CH
2021				
2022	900665.5		2200	2200
2023	1233912		2420	2420
2024	1690459		2662	2662
2025	2315929		2928.2	2928.2

AC project ratio	CH
2021	1000
2022	1100
2023	1210
2024	1331
2025	1464.1

Figure 28: Excel screenshot of goal programming model Scenario 1, Iteration 2



Assume
Same office electricity consumption rate of 146.4 kWh/sq m
Project area growth >10%, <37%
Increase in annual parameter efficiency by 5%
AC projects >= 0.5 CH projects

Office energy **146.4**

	LED	AC	CH	>=	2000	
2021	769345	17268	34535	821148		
2022	1054003	23657	47313	1124973		
2023	1443984	32410	64819	1541213		
2024	1978258	44401	88802	2111462		
2025	2710214	60830	121659	2892703		
	7955805	178565	357130	8.49E+06	<=	8.49E+06

Small-Med Buildings			
385	9	17	411
527	12	24	562
722	16	32	771
989	22	44	1056
1355	30	61	1446
3978	89	179	4246

Large Buildings		
77	1.7	3.5
105	2.4	4.7
144	3.2	6.5
198	4.4	8.9
271	6.1	12.2
796	18	36

CO2 reduction (t CO2e/kWh)	LED	AC	CH						
2021	0.0025475	3.1E-05	0.00086	286928	77.8239	4326.63			
2022	0.0026748	3.2E-05	0.0009	412745	111.95	6223.86			
2023	0.0028086	3.4E-05	0.00094	593734	161.04	8953.03			
2024	0.002949	3.6E-05	0.00099	854087	231.656	12878.9			
2025	0.0030965	3.7E-05	0.00104	1228604	333.236	18526.3	3.43E+06	>=	3.41E+06
				3.38E+06	**9.16E+02**	**5.09E+04**			

Cost savings (THB/kWh)	LED	AC	CH				
2021	17.532595	0.22242	7046.8	2E+09	562276	3.6E+10	
2022	18.409225	0.23354	7399.14	2.8E+09	808834	5.1E+10	
2023	19.329686	0.24522	7769.1	4.1E+09	1163507	7.4E+10	
2024	20.29617	0.25748	8157.55	5.9E+09	1673705	1.1E+11	
2025	21.310979	0.27035	8565.43	8.5E+09	2407625	1.5E+11	4.42E+11
				2.32E+10	**6.62E+06**	**4.19E+11**	

Electricity savings (GWh/kWh)	LED	AC	CH						
2021	4.383E-06	5.3E-08	1.1E-06	493.683	0.13388	5.45266			
2022	4.602E-06	5.6E-08	1.1E-06	710.163	0.19258	7.84365			
2023	4.832E-06	5.8E-08	1.2E-06	1021.57	0.27703	11.2831			
2024	5.074E-06	6.1E-08	1.2E-06	1469.53	0.3985	16.2307			
2025	5.328E-06	6.4E-08	1.3E-06	2113.92	0.57325	23.3479	2138	>=	2138
				5.81E+03	**1.58E+00**	**6.42E+01**			

Cost (THB/kWh)	LED	AC	CH						
2021	0.0008351	0.00033	0.00034	94063.1	825.947	1738.32			
2022	0.0007934	0.00031	0.00033	122423	1074.97	2262.42			
2023	0.0007537	0.00029	0.00031	159334	1399.07	2944.54			
2024	0.000716	0.00028	0.00029	207373	1820.89	3832.32			
2025	0.0006802	0.00027	0.00028	269896	2369.89	4987.76	8.76E+05	<=	1.48E+09

<37%	LED	AC		CH
2021				
2022	1054003		23656.68004	47313.4
2023	1443984		32409.65166	64819.3
2024	1978258		44401.22277	88802.4
2025	2710214		60829.6752	121659

>10%	LED	AC		CH
2021				
2022	846280		18994.41463	37988.8
2023	1159403		26022.34805	52044.7
2024	1588383		35650.61682	71301.2
2025	2176084		48841.34505	97682.7

AC project ratio	CH
2021	17267.6
2022	23656.7
2023	32409.7
2024	44401.2
2025	60829.7

Figure 29: Excel screenshot of goal programming model Scenario 1, Iteration 3

```python
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

#Scenario 1 results
x = (3.59,3.59,3.43) #CO2 reduction
y = (3.88,3.88,44.2) #Cost savings
z = (6.18,6.18,5.88) #Electricity savings

#Scenario 2 results
a = (3.59,3.41,3.41) #CO2 reduction
b = (6.09,47.6,47.9) #Cost savings
c = (6.17,5.84,5.84) #Electricity savings

fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')
ax.plot(x,y,z,marker="o",color="g",label="Scenario 1")
ax.plot(a,b,c,marker="o",color="b",label="Scenario 2")

plt.rcParams["font.family"] = "serif"

ax.set_title("Office LCB Scenario Comparison",loc='left')
ax.set_xlabel("CO2 Reduction (x10^6 tCO2e)")
ax.set_ylabel("Cost Savings (x10^10 THB)")
ax.set_zlabel("Electricity Savings (x10^9 kWh)")
ax.set_xlim(3,4)
ax.set_ylim(0,50)
ax.set_zlim(2,7)
ax.set_xticks([3.0,3.4,3.8])
ax.set_yticks([0,20,40])
ax.set_zticks([2,4,6])

fig.set_size_inches(6, 6)
plt.legend(loc='best')
plt.savefig("Thesis.pdf")
plt.show()
```

Figure 30: Python code for 3D plot

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