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Article

Life-Cycle Analysis of Building Retrofits at the Urban Scale—A Case Study in United Arab Emirates

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Abstract: A consensus is forming among experts that the best way to achieve emissions' reduction in the near and mid-term is increasing the demand-side energy efficiency—this is especially true in developing countries where the potential for demand reduction is significant and achievable at relatively lower cost. Enhanced energy efficiency also reduces energy costs and can result in a financial benefit to end-users, if the life-cycle value of energy savings offsets the upfront cost of implementing the measure. At the same time, reducing energy demand translates into lower pull for fossil fuel import and supply/distribution capacity expansion. An ideal candidate for the implementation of demand-side energy efficiency measures is the building sector, since it contributes to a large extent to the total amount of greenhouse gases (GHGs) emitted worldwide. In most developing countries, the contribution of the building sector to the total national GHG emissions is significantly higher than the worldwide average. This is in part due to the lower level of industrial activity. Other drivers of the high emissions of the building sector are the inefficiency of the envelope and technical systems of the existing buildings, as well as harsh climatic conditions requiring the use of energy intensive air-conditioning equipment. The United Arab Emirates (UAE) currently have the highest ecological footprint per capita in the world. The Emirate of Abu Dhabi, the focus of this study, can be expected to have a footprint that is even higher, being the largest economy and the major oil producer among the seven Emirates. In addition to the environmental consequences of unrestrained energy consumption, the fact that energy prices are heavily subsidized in

Abu Dhabi results in a significant financial burden for the government. In the UAE and the Emirate of Abu Dhabi, the air-conditioning load in buildings is the ideal target for demand-side management because it constitutes more than 60% of the total energy consumption. However, many sources of uncertainty still remain. How should we assess the life-cycle cost/benefit of candidate demand-side interventions? Which ones to choose in order to maximize national utility? This study will start to answer those questions by using a detailed engineering model of a typical Abu Dhabi building as specified by the Emirate's Urban Planning Council. Using the model building as a baseline, we then proceed to evaluate the energy impact of different retrofits through numerical simulation. We present a novel Marginal Abatement Cost Curve (MACC) for the Emirate of Abu Dhabi focusing exclusively on demand-side measures having an impact on the air-conditioning load. A surprising number of the abatement levers analyzed in this study exhibit a positive net present value (NPV), if the cost-reflective price of electricity is used for the life-cycle assessment.

Keywords: energy efficiency; existing buildings; marginal abatement cost curve; energy modeling

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1. Introduction

Energy efficiency is a well-established option to decouple economic growth from the increase in energy consumption and thus reduce greenhouse gas (GHG) emissions by cutting the amount of energy required for a particular amount of end-use energy service. Apart from being a sound part of the environmental and climate change agenda, increased energy efficiency can contribute to meeting crucial energy policy goals such as improved security of supply, economic efficiency, and increased business competitiveness coupled with job creation and improved consumer welfare.

In this study we will develop a life-cycle analysis of energy efficiency retrofits in the existing buildings sector of Abu Dhabi. Abu Dhabi is one of the seven Emirates of the United Arab Emirates (UAE). The per capita greenhouse gas emissions of the UAE are extremely high and the situation is most acute in Abu Dhabi, the largest and wealthiest of the Emirates. In addition to the environmental consequences of unrestrained energy consumption, the fact that energy prices are heavily subsidized in Abu Dhabi results in a significant financial burden for the government. Furthermore, since peak demand determines the capacity of the supply/transmission/distribution system, any reduction in peak load will be valuable in terms of minimization of investments in future asset expansions and optimization of the existing infrastructure.

1.1. Context and Motivation

The United Arab Emirates currently have the highest ecological footprint per capita in the world [1]. The Emirate is expected to have a footprint that is even higher, having the largest economy and the highest level of oil production among the Emirates. Smeetsa and Bayar [2] developed a dynamic multi-sectorial econometric model of CO_2 emissions specifically for Abu Dhabi. The model estimates current annual emissions of the Emirate of Abu Dhabi ("the Emirate" in short, hereafter) to be 81.8 million tons of CO_2 (56% of the total UAE emissions). According to this model, the Emirate's emissions are expected to grow by 85% over the next decade, under a business-as-usual growth scenario defined by the Abu Dhabi Economic Vision 2030 [3].

In addition to the environmental consequences of unrestrained energy consumption, the fact that energy prices are subsidized in the Emirate results in a significant financial burden for the government. A recent Booz and Company study [4] estimated the real cost of the production of a kWh of electricity in a typical GCC country to be around $0.12, thrice the actual retail rate of $0.04 per kWh in the Emirate. Finally, the Emirate is exhausting its sources of inexpensive gas and may soon need to rely on imported Liquid Natural Gas (LNG). The resulting marginal cost of electricity is expected to be high. Demand-Side Management is clearly a more attractive option than LNG.

A Comprehensive Demand-Side Management Study, performed in 2009, established the baseline for electricity usage patterns by typology, sector, and customer segments. Figure 1 shows the sectorial decomposition of energy use. The study recommended a range of energy efficiency measures and strategies [5]. The study proposed to focus the DSM strategy on Commercial, Residential and Government sectors which represent 87% of the total load demand. In these sectors, air-conditioning load represents close to 70% of the total electricity consumption according to a recent study by the Municipality of Abu Dhabi City [6]. Figure 2 displays a break-down of electricity consumption per end-use according to the aforementioned ADM study.

The significant role of air-conditioning in the Emirate's load is confirmed by a regression analysis performed at Masdar Institute (e.g., [7]) as displayed on Figure 3. This study shows that the impact of air-conditioning is highest when the system is experiencing its peak demand, *i.e.*, during the summer months.

Weather features are essential determinants in energy efficiency projects. Two weather indicators are sufficient to characterize Abu Dhabi's climate: temperature (temperature) and humidity (relative). The plots in Figure 4, generated using the Climate Consultant software package based on the IWEC weather data, display average daily profile of temperature and humidity for each month of the year. Humidity at night reaches 80% in winter and 70% in summer. Furthermore, the UAE has the highest wet-bulb design temperature in the world, which is 30.6 °C, making it one of the most challenging places for maintaining indoor human comfort. Dry bulb design temperature is 45.0 °C per ASHRAE's Handbook of Fundamentals [8]. These extreme conditions explain the almost mandatory role of air-conditioning in the daily life of the residents and its significant impact on the electrical consumption amount and variability.

Based on private communications and reports, we estimate that explicit and implicit energy and water subsidies cost the Emirate's government more than $2.5 billion per year. Abandonment of energy subsidization and/or introduction of energy taxation, as is commonly practiced in other countries, is a sensitive issue in the Emirate (see also [9,10]). At the same time, the low prices of energy have triggered large-scale over-consumption of energy commodities, and a lacking awareness of the scarcity of utilities among the end-users. In the absence of taxation as a feasible policy option in the short to medium run, the government is looking into several strategies to reward energy efficient behavior and energy efficiency retrofits. In support of those policies, it is important to understand the impact of planned interventions.

Figure 1. Sectorial decomposition of energy use.

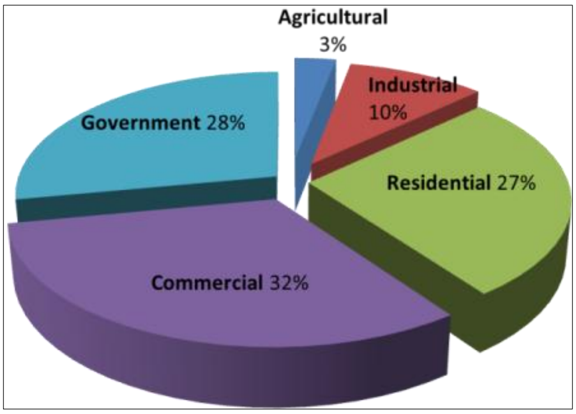


Figure 2. Break-down of electricity consumption per end-use.

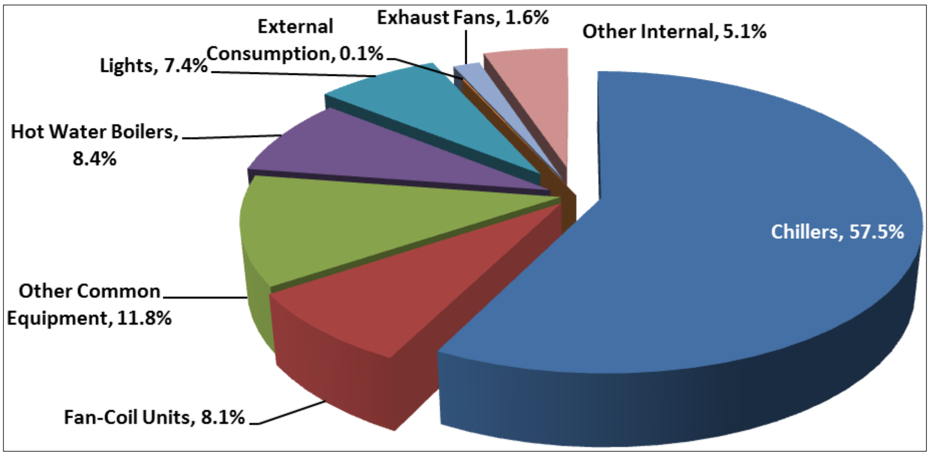


Figure 3. Contribution of air-conditioning load—driven by temperature, humidity and solar gains—to the electricity consumption profile for the year 2010 (1 January to 31 December). Note that a portion of the base-load is also due to air-conditioning (equipment running year-round).

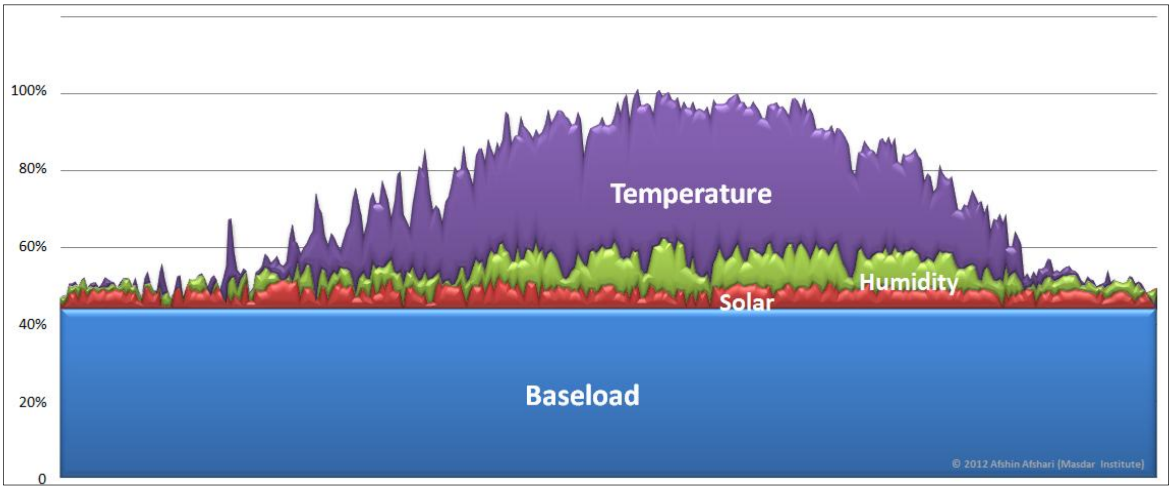
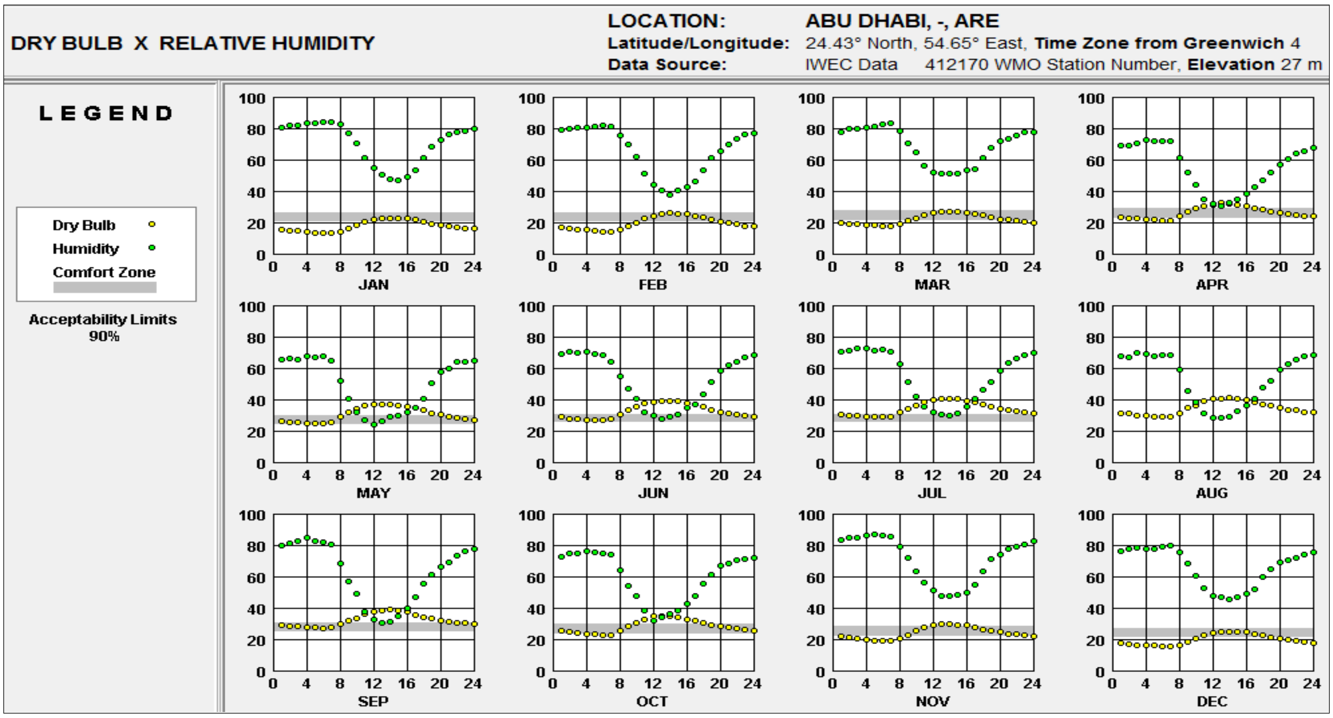


Figure 4. Monthly average profiles of temperature and humidity in Abu Dhabi.



As is common across most of the Gulf Cooperation Council (GCC) countries, one of the mechanisms through which the Emirate's government distributes the wealth from natural resources to its population is the below-market pricing of energy. As a result, utility prices are artificially kept low in Abu Dhabi. For instance electricity is sold at a flat rate of 0.04 $/kWh to all end-users—except UAE nationals who benefit from a further reduced rate [11]. In comparison, Dubai's Electricity and Water Authority [12] charges, since 1 January 2011, a progressive ("slab") rate varying between 0.06 and 0.10 $/kWh depending on monthly usage.

1.2. Approach

Building energy efficiency is increasingly recognized as the optimal way to attack CO_2 emissions linked to climate change. A 2007 study by McKinsey [13] found that simple technologies such as lighting energy use, better building glazing and insulation, and more efficient heating, ventilation, and air-conditioning (HVAC) systems could significantly reduce carbon dioxide emissions and still represent a net economic gain for society.

Generally, improvements in the energy efficiency of the building envelope are expensive because they require labor-intensive modifications such as addition of thermal insulation and replacement of windows. Therefore, the payback periods of most building envelope retrofits are long. In these instances, the building envelope retrofits may be justified for reasons other than energy efficiency such as increase in indoor thermal comfort or reduction of moisture. However, there are cases where retrofits of building envelope can be justified based solely on energy conservation. Some of these retrofit measures are:

- Insulation of poorly insulated envelope components;
- Window improvement/replacement;

- Improvement of envelope air-tightness;
- Cool roof retrofit.

Some of the most common retrofits of the AC system include:

(1) Adjusting up thermostat set-point: When appropriate, increasing cooling temperature set-points can be considered.
(2) Retrofit of constant air volume systems: For commercial buildings, variable air volume (VAV) systems should be considered when the existing HVAC systems rely on constant volume fans.
(3) Installation of heat recovery systems: Heat exchangers can be installed to recover thermal energy from air handling unit (AHU) exhaust air streams.
(4) Retrofit of central cooling plants: New chillers tend to be more energy-efficient and easier to control and operate.
(5) Re-commissioning of the controls: Generally, the following re-commissioning measures can be envisaged:

    - Operating the systems only when required for comfort, safety or health reasons (e.g., no ventilation during unoccupied periods);
    - Eliminate overcooling to improve comfort and save energy;
    - Reduce reheat in the AHU;
    - Provide free cooling whenever possible (e.g., by heat recovery systems or economizer);
    - Reduce or better regulate the amount of fresh air delivered by the AHU.

It should be noted that there is a strong interaction among various components of the AC system. In addition, retrofits of the electrical systems (lighting, office equipment) decrease space cooling loads and therefore further reduce the electrical energy use in the building. These cooling energy reductions should be accounted for. Therefore, a whole-system analysis approach should be preferred whenever possible.

Energy conservation retrofits are deemed cost-effective based on predictions of post-retrofit energy and cost savings. In principle, the estimate of the retrofit energy savings can be obtained by simply comparing the actual energy consumption before and after the retrofit. In our case, we will analyze the before/after change in energy consumption via a detailed building energy model.

Energy modeling tools can be classified into either forward or inverse methods. In the forward approach, the energy predictions are based on a detailed engineering description of the building and its technical systems. These models require prior knowledge of certain information such as geometry, location, construction details, HVAC system type, internal gains and operational schedules. Most of the existing detailed energy simulation tools such as DOE-2, TRNSYS, and EnergyPlus follow the forward modeling approach. In the inverse approach, the energy analysis model attempts to deduce representative building features such as the building base-load, or the building time constant using measured energy use, weather, and relevant performance data. In general, the inverse models are less complex to formulate than the forward models.

However, the flexibility of inverse models is typically limited by the simplified formulation of the representative building parameters and the low accuracy of the building performance data. Most of the existing inverse models rely on regression analysis tools to identify the building parameters (e.g., [7]).

It should be noted that tools based on the forward or inverse approaches are suitable for other applications. Among the common applications are verification of energy savings actually incurred from energy conservation measures, diagnosis of equipment malfunctions and efficiency testing of building energy systems.

For this analysis, we will be using EnergyPlus, a research-oriented forward modeling platform. EnergyPlus is a dynamic modeling platform using numerical methods to determine energy transfer among various building sub-systems. The simulation runs with hourly or sub-hourly time steps to estimate adequately the effects of thermal inertia, due, for instance, to energy storage in the building envelope or the chiller plant. A detailed physical specification of the building properties (including building geometry, building envelope construction details, HVAC equipment type and operation, and operational schedules) is required by EnergyPlus. This specification requires a high level of engineering expertise and is generally suitable to simulate large buildings with complex HVAC systems and control strategies that are difficult to model using simplified energy analysis tools. To adequately estimate energy savings from energy-efficiency measures, building energy simulation tools have to be calibrated using actual measured energy data (monthly utility bills, for instance).

Following model calibration, we proceed to simulate different candidate retrofit measures. For each retrofit scenario, the resulting annual energy consumption is compared to the baseline (unaltered) building energy consumption. Finally we perform a life-cycle analysis involving carbon emissions and cost. This results in a Marginal Abatement Cost Curve which can be used as a decision support tool for the design urban-level demand-side management programs.

In [14], Rysanek and Choudhary presented a similar approach, for a single office building in the UK. The authors used sequential optimization and exhaustive search of building refurbishment options based on a custom building energy model developed on a TRNSYS platform. In [15], Radhi and Sharples presented a carbon emissions study for UAE's residential sector. The authors modeled the energy savings resulting from different projected retrofit interventions and predicted the evolution of the carbon emissions in the UAE residential sector. To do this they build a bottom-up model of the residential sector composed of several building typologies. However, they did not develop a MACC since they did not investigate the cost of the retrofits.

2. Method

The objective of this research is the development of a framework according to which, energy efficiency retrofit measures can be assessed in the existing building sector of the Emirate of Abu Dhabi. Energy savings can be estimated in a relatively straightforward manner by applying retrofits to the existing building model. These retrofits have to be evaluated not only based on the savings that can be achieved and the CO_2 abatement potential, but also based on the life cycle cost/benefits. An illustrative way of depicting the above is the Marginal Abatement Cost Curve, which is presented in this study. Based on the analysis of a typical building in Abu Dhabi's downtown area, we estimate the impact that different retrofit measures would have on the annual electricity load as well as the peak demand, focusing exclusively on the air-conditioning component of the load. The results are then extrapolated to the entire Emirate.

Our analysis is comprised of the following tasks:

- Development and calibration of a detailed engineering model on the basis of the data provided by the Urban Planning Council for a typical building in the Emirate of Abu Dhabi [16];
- Simulation-based analysis of the impact of candidate energy efficiency measures on the energy performance of the aforementioned typical building;
- Estimation of the potential CO_2 emissions abatement resulting from the implementation of the candidate measures;
- Life Cycle Cost/Carbon assessment of the candidate measures;
- Extrapolation of the typical building to the whole Emirate and development of several Marginal Abatement Cost Curves (MACCs).

The measures evaluated in this study concern either the retrofit of the building envelope or the replacement of the air conditioning equipment. Measures such as lighting replacement, HVAC maintenance or retro-commissioning of the building management system are excluded from the scope.

2.1. Defining a Business as Usual (BAU) Building

The first step of the current work is the consistent specification of a Business As Usual (BAU) building representative of an average building in the Emirate. Unless the detailed description of the BAU is at hand, the project cannot generate reliable results given the fact that every kind of retrofit applied has to be compared and evaluated in terms of energy savings and CO_2 abatement in comparison to the baseline *i.e.*, the BAU.

The data required for this task were obtained from the Energy and Water Benchmarking Study which was prepared in 2010 at the request of the Urban Planning Council in order to develop a sustainability rating system for the building sector in Abu Dhabi, *i.e.*, the Estidama Pearl Design System. The establishment of a BAU benchmark of Abu Dhabi energy and water consumption levels for application to the Pearl Design System Rating Method was the main objective of the Arup—consulting firm who authored the report.

In order to develop the BAU models, Arup undertook a number of site inspections. They also used databases obtained from the UPC to get building information such as footprint, use and floor number whereas the Abu Dhabi Distribution Company (ADDC) provided complementary information regarding the metered electricity consumption. From this study, the basic characteristics of the typical existing building sector in Abu Dhabi were derived and are used herein. The development of the detailed model of the prototypical building required a lot of time and effort. To build the detailed model, we needed to define, in great detail, the envelope of the building as well as the HVAC system, lighting and miscellaneous equipment. We also needed information about occupancy, control set-points and schedules and weather. Since the report and other related files put at our disposal did not contain a complete set of specifications and since our efforts to trace the original authors were unsuccessful, in order to fully parameterize our BAU model, we had to go through a long and arduous process of model calibration whereby the unknown model parameters were tuned until the simulated energy consumption of the different building sub-systems matched the monthly values tabulated in the UPC-Arup report.

Once the model is fully specified, it can predict the energy performance of the building. This property of the model is significant because it correlates the construction and operation of the building to its performance. The retrofits change the performance by modifying the building specifications. This is going to be examined later in this study by undertaking a parametric analysis of the impact of each retrofit on the final energy consumption.

Of the three typical buildings proposed by Arup we selected the mixed-use office type. We opted for this simplified approach because the other building types (residential and retail) present a very similar annual load profile, although their energy intensity per unit of floor area may vary. In other words, the total system load is appropriately represented by the aggregation of a certain number of mixed-use office buildings (more on this below). The main features of the selected BAU building, modeled in EnergyPlus, are listed below:

- Length, width and height: 40 m, 40 m, 52.5 m;
- Number of floors: 15 (top floor is plant room);
- Total floor area: 23,312 m^2;
- Volume: 81,593 m^3;
- Windows applied for all the 13 middle floors and one side of the ground floor: continuous horizontal glazing with an overall window to wall ratio of 70%;
- Infiltration rate: 0.3 ACH (air changes per hour);
- People density: 0.085 person/m^2 (approx. 12 m^2/person);
- Minimum fresh air: 10 L/s-person (liter per second per person);
- Equipment intensity: 15 W/m^2, applied to all the non-common areas of the ground and middle floors;
- Lighting intensity: 10 W/m^2;
- Chiller COP: 2.8 (constant);
- Heat recovery: sensible only, 65% effectiveness;
- Main occupancy period: 6 am–8 pm;
- Envelope *U*-values: 1.71 W/m^2 K for the wall, 0.53 W/m^2 K for the roof;
- Glazing characteristics: *U*-Value = 2.4 W/m^2 K, SHGC (solar heat gain coefficient) = 0.36.

2.2. Energy Efficiency Retrofits

Having defined the BAU and calculated the baseline energy consumption, the next step was to start applying different retrofits. Retrofits can be applied on the envelope, such as adding insulation in order to improve the wall resistance or replacing the windows with better ones (lower *U*-Value) in order to reduce external heat gains. The air-tightness of the building also has a significant impact on the external heat gains. Also, of course, there is always need to decrease the internal gains. The improvement of the cooling equipment is the paramount retrofit when the objective is to reduce the air-conditioning load, as in this study. However, unless the heat gains decrease, improving the performance of the cooling equipment (COP) will fail to yield its full potential.

In general, the constituents of the cooling load are the following:

- Space cooling load corresponding to internal and external gains (sensible + latent);
- Load due to mechanical ventilation (or fresh air load).

The sensible cooling load refers to the energy demand directly responsible for keeping the building's indoor dry bulb temperature close to a prescribed comfort set-point (e.g., 24 °C), while the latent cooling load is the energy required to keep the indoor air humidity close to a prescribed comfort set-point (e.g., 55% relative humidity).

Any decrease in the peak summer day load also potentially results in a reduction of the total cost of the equipment, since the peak load is the basis for equipment sizing. That is why it is important to investigate both the annual energy savings and the reduction of the peak demand.

The retrofits tested aim at reducing the different heat gains. They are the most effective ones for this purpose and can be implemented with relative ease, albeit at a cost:

- Enhancement of wall insulation;
- Enhancement of the glazing (replacement);
- Enhancement of chiller COP (replacement);
- Enhancement of envelope air-tightness;
- Increase of the cooling set-point temperature;
- Enhancement of roof insulation;
- Cool roof.

All these retrofits affect both the total annual electricity consumption and the peak load. The selected retrofits as well as the resulting improvement of the energy performance of the building are presented in subsequent sections.

2.3. Estimation of the Costs

This part of the investigation is essential for the financial evaluation of the retrofits applied. The majority of the selected retrofits have a high capital cost and in some cases it might not be financially sustainable for the rational investor to invest the required sum upfront, considering the future savings stream. In our study, the Net Present Value (NPV) of each one the retrofits is calculated in order to understand the life-cycle cost/benefits.

The majority of the cost data for each one of the retrofits were obtained from the National Residential Efficiency Measures Database of the National Renewable Energy Laboratory [17] which is a publicly available, centralized resource of residential building retrofit measures and costs for an average US building. In the absence of a UAE retrofit cost database, it is assumed here that the US costs provide an acceptable approximation.

The next step after the calculation of the capital costs is the calculation of the NPV of the investment which is also required for the development of the MACC. Calculations for the capital cost investment and the NPV of each retrofit will be presented later in the study.

2.4. Derivation of the Marginal Abatement Cost Curve (MACC)

The MACC can provide the policy makers with an understanding of the significance and cost of each possible method of reducing emissions and of the relative importance of different technologies and sectors. The information that can be obtained from a MACC is the amount of CO_2 emissions that can be abated ("abatement potential") by changing a Business as Usual (BAU) situation using an abatement "lever", as well as the cost of abating 1 ton of CO_2 after applying the specific lever. In other words, a MACC illustrates the impact of low carbon options compared to the BAU situation. In general, typical options in a MACC include switching to clean/renewable energy, carbon capture and sequestration, improving demand-side energy efficiency, *etc.*

The marginal abatement cost is plotted on the y-axis, and the abatement projects are ranked against this metric from lowest cost to highest cost. The width of the column is equal to the potential (maximum) amount of carbon that can be saved by the project, and the area of each column equal to the total cost or benefit of the project. Negative MACC values indicate that the project is self-financing (*i.e.*, the NPV is positive), whereas positive MACC values require judgment against the cost of BAU/inaction. All these levers with the negative values (positive NPV) are the ones that we are most interested in, since future positive cash flows during the life of the measure are deemed sufficient to pay back for its upfront cost. By adopting such measures the rational investor not only reduces the CO_2 emitted but also makes a "profit".

In order to develop the MACC for the Emirate of Abu Dhabi, first, the potential abatement of CO_2 emissions has to be calculated for the typical building(s) as well as the respective life cycle costs. Thereafter, we extrapolate our results to the level of the Emirate. In general, the steps to be followed are the following:

Step 1: Building Model Development

In order to calculate the energy consumption of the building sector and the potential improvement of its performance, we model the building for the BAU as well as for different retrofit scenarios. After applying each new retrofit, the decrease in energy consumption is recorded. At the end of this step, we obtain the annual reduction in the load (energy/peak) for each retrofit.

Step 2: CO_2 Emissions Calculation

Having obtained the electricity savings, we can calculate the potential abatement of CO_2 resulting from the operation of the building modeled above, by multiplying the energy consumption with the carbon intensity of electricity in the emirate of Abu Dhabi.

Step 3: Financial Evaluation—Life Cycle Assessment of the Respective costs

Financial evaluation methods facilitate comparisons among candidate investments options. Generally, the same methods can be used to compare investments on the supply-side and on the demand-side (energy efficiency). We will use the NPV method to assess the life-cycle cost/benefit of each measure over an assumed 30-year life. After calculating the costs we can proceed to the following step which is the construction of the MACC.

Step 4: Development of the MACC

The basic idea behind the development of a MACC is very simple and relies on the calculation of financial impact and carbon abatement potential. For each lever, if we divide the total cost by the total amount of CO_2 abated then we obtain the cost per ton of CO_2 ("tCO_2") abated. The width of each column (corresponding to a given lever) represents the annual abatement potential of the lever.

3. Energy Impact of Retrofits

3.1. BAU Energy Performance

In Table 1 below, we present the breakdown of the total electricity consumption of the BAU building for the whole year. These numbers were obtained after running the simulation on the fully calibrated model—using EnergyPlus software and Abu Dhabi weather data.

Table 1. Annual electricity consumption for the Business as Usual (BAU) building per load type.

Office BAU	Chiller (kWh)	Pumps (kWh)	Fans (kWh)	Lights (kWh)	Equip (kWh)
January	102,011	36,734	39,862	116,948	101,457
February	119,031	33,706	36,004	106,583	93,840
March	167,483	38,190	39,862	121,060	105,722
April	202,784	37,108	38,576	111,577	95,364
May	298,871	38,345	39,862	121,060	105,722
June	357,550	37,108	38,576	116,235	101,762
July	426,926	38,345	39,862	113,927	101,457
August	433,243	38,345	39,862	121,060	105,722
September	394,735	37,108	38,576	112,668	99,629
October	285,871	38,345	39,862	117,494	103,590
November	203,720	37,108	38,576	116,235	101,762
December	124,309	37,945	39,862	112,836	97,192
Total 6,635,159 kWh	3,116,531	448,385	469,340	1,387,683	1,213,219

The total electricity consumption of the BAU building is 6635 MWh per year. The chiller load is almost half of the total electricity consumption accounting for 47%. Lights and equipment together account for almost 40% and the remaining 14% is the electricity consumption of the fans and the pumps. Therefore the total cooling load (chiller + pumps + fans) represents 61% of the annual electricity use (see Figure 5).

Figure 5. Annual electricity consumption per load type.

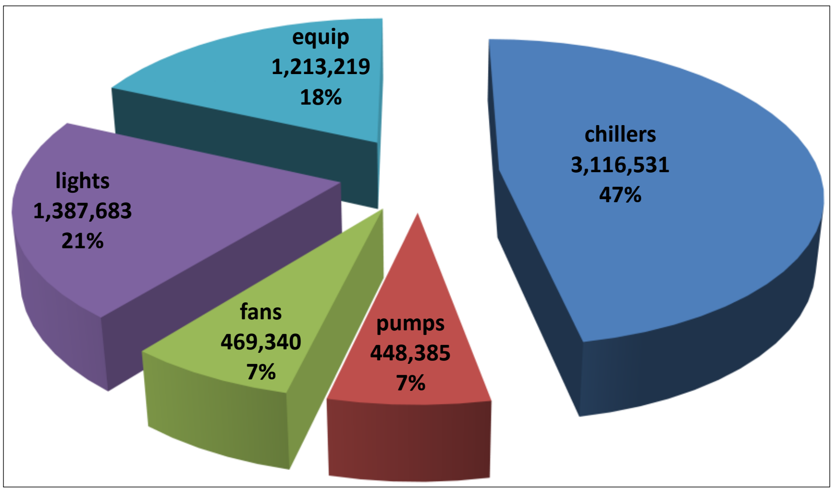


Table 1 details the monthly energy consumption of the BAU building for the whole year. Obviously, the total cooling load is the sum of chiller, pumps and fans loads.

The annual cooling load is 4034 MWh and it is the main target of our retrofits. As far as the peak cooling load is concerned, it reaches its highest value in August: 1107 kW or 316 tons of refrigeration. As previously mentioned, the peak load is important since on its level depends the sizing of the cooling equipment and in a larger scale, the characteristics of the whole electricity grid (aggregate peak load).

3.2. Implementation of Retrofits

In this section we present the energy performance of the building after the application of each retrofit as well as the corresponding decrease of the cooling load.

3.2.1. Air Tightness

By improving the airtightness of a building we can significantly decrease the external heat gains and improve the total energy performance of the building. An improvement in the air-tightness reduces directly the cooling load, *i.e.*, chiller, fans and pumps. According to the Arup report, the airtightness of the BAU is 0.3 ACH (Air Changes per Hour). 4 different levels of air-tightness retrofit are considered, *i.e.*, 0.25 ACH, 0.2 ACH, 0.15 ACH and 0.1 ACH. In Tables 2a and 2b, we present, for each retrofit case, the new annual cooling load and cooling peak load as well as the percent reduction in comparison to BAU.

Table 2a. Peak cooling load and percentage reduction for air-leakage retrofits.

Cooling	BAU	0.25 ACH	0.2 ACH	0.15 ACH	0.10 ACH
Peak (kW)	1107	1086	1052	1032	1010
% reduction	-	2%	5%	7%	9%

Table 2b. Annual Cooling load and impact of air-leakage retrofits.

	BAU	0.25 ACH	0.2 ACH	0.15 ACH	0.10 ACH
Annual Load (MWh)	4034	3979	3922	3867	3811
% reduction	-	1.4%	2.8%	4.1%	5.6%

This measure has a more pronounced impact on peak.

3.2.2. Cooling Temperature Set-Point

The cooling set-point for the BAU building is set to 22 °C. This temperature set-point, although quite common in Abu Dhabi offices and residences, is on the low side and can be increased by several degrees without a significant impact on perceived thermal comfort. 4 levels of retrofit were tested, increasing the set-point by one degree each time, *i.e.*, SP23, SP24, SP25, SP26. In the Tables 3a and 3b, we present the percentage reduction of the cooling peak load and the percentage change in the annual cooling load respectively.

Table 3a. Percentage reduction of the cooling peak load.

	BAU	SP23	SP24	SP25	SP26
Peak (kW)	1107	1068	1034	997	961
% reduction	-	3.6%	6.2%	9.9%	13%

Table 3b. Percentage reduction of the annual cooling loads.

	BAU	SP23	SP24	SP25	SP26
Annual Load (MWh)	4034	3704	3395	3103	2827
% reduction	-	8%	16%	23%	29%

In this case, the reduction in annual load is more than twice the reduction in peak.

3.2.3. Chiller COP

The COP for the BAU is 2.8 (assumed independent of part-load ratio). We consider 5 levels of retrofit corresponding to COP vales 3.0, 3.3, 3.5, 3.7 and 4.0. In the Tables 4a and 4b we present the percentage reduction of the cooling peak and annual load respectively.

Table 4a. Reduction of cooling peak load for different cooling equipment (COPs).

	BAU	COP3/ SEER11	COP3.3/ SEER13	COP3.5/ SEER14	COP3.7/ SEER16	COP4/ SEER17
Peak (kW)	1107	1041	958	907	864	807
% reduction	-	6.1%	13.4%	18.1%	22%	27%

Table 4b. Reduction of annual cooling load for different COPs.

	BAU	COP3/ SEER11	COP3.3/ SEER13	COP3.5/ SEER14	COP3.7/ SEER16	COP4/ SEER17
Load (MWh)	4034	3826	3562	3411	3276	3099
% reduction	-	5%	12%	15%	19%	23%

3.2.4. Glazing

Different types of glazing are tested in replacement of the existing one. In our BAU, 70% of the building's façade is glazed. As a result, the replacement of the existing glazing with a good quality window with a low *U*-value and Solar Heat Gain Coefficient (SHGC) has a non-negligible impact on the cooling consumption although the window type used in the BAU is of a relatively good quality (*U*-Value of 2.4, SHGC of 0.36). In order to have realistic retrofits we investigated only two different types of glazing with better performance than the existing one.

The two different window types tested are:

- GLZ1 (U = 1.47, SHGC = 0.3): Double-Pane, Low-Gain Low-E, Insulated Frame, Argon Fill;
- GLZ2 (U = 1.7, SHGC = 0.3): Double-Pane, Low-Gain Low-E, Insulated Frame, Air Fill.

The impact of the retrofits on peak load and annual consumption is given in Tables 5a and 5b. This retrofit is moderately effective, however it requires the very intrusive replacement of all existing windows and because the existing windows are already of decent quality, any improvement is bound to be very expensive. Because of these practicality and cost concerns, window retrofits will not be considered in the remainder of this study.

Table 5a. Reduction of cooling peak load for glazing retrofits.

	BAU	GLZ1	GLZ2
Peak (kW)	1107	1061	1067
% reduction	-	4.2%	3.6%

Table 5b. Reduction of annual cooling energy for glazing retrofits.

	BAU	GLZ1	GLZ2
Load (MWh)	4034	3847	3892
% reduction	-	4.6%	3.5%

3.2.5. Opaque Partition Insulation

The retrofit technique tested is wall sheathing. According to this technique, we add insulation material (extruded polystyrene) between the innermost and outermost layers of the external wall. The insulation type and total wall *U*-Values for the different retrofits are provided in Table 6.

Table 6. Different types of wall insulation retrofits.

Insulation layer added	Final Wall *U*-value ($W/m^2 \cdot K$)
R-5 XPS, thickness: 30 mm	0.705
R-10 XPS, thickness: 50 mm	0.444
R-15 XPS, thickness: 80 mm	0.324

In general the insulation of the walls plays an important role to the energy performance of the buildings. However, since in our BAU building the window-to-wall ratio is high, most of the façade is covered by glazing and not walls and the response of the cooling load to the insulation retrofits is low. The impact on peak load and annual consumption is given in the Tables 7a and 7b.

Table7a. Reduction of cooling peak load for wall insulation retrofits.

Peak Load	BAU	R5 XPS	R10 XPS	R15 XPS
(kW)	1107	1084	1079	1077
% reduction	-	2.1%	2.5%	2.8%

Table 7b. Reduction of annual cooling energy for wall insulation retrofits.

Annual Load	BAU	R5 XPS	R10 XPS	R15 XPS
MWh	4034	3960	3938	3928
% reduction	-	1.8%	2.4%	2.6%

Since the BAU building already has a well-insulated roof and the ratio of the roof area over the total floor area is even smaller than the ratio of the vertical wall area over total floor area, unsurprisingly, the impact of roof insulation retrofits is almost negligible. We also tried to improve the roof albedo

(1-absorptivity). A cool roof retrofit (light color paint) is tested whereby albedo is increased from the current 0.4 to 0.7. Given the limited roof area compared to the total floor area this retrofit has only a minor impact.

We will not consider roof retrofits in the remainder of this study, but pause to note that in a low-rise building they would definitely be worthwhile, in particular the cool roof retrofit which has a low cost.

4. Life-Cycle Assessment

Since we do not have access to a retrofit cost database for Abu Dhabi, for the calculation of the capital costs of each retrofit we used the National Residential Efficiency Measures Database [17].

The National Residential Efficiency Measures Database was developed by the National Renewable Energy Laboratory (NREL) on behalf of the US Department of Energy. The purpose of that project was to provide a national unified database of residential building retrofit measures and associated costs. The database is freely accessible. The user first chooses the baseline feature (BAU) and then the envisaged modification. The database then provides the cost of the retrofit in \$ or \$/ft^2.

For the calculation of the cost of replacing the chiller, we follow the following principles. First of all, for each retrofit there is one fixed and one normalized cost. The fixed cost is constant for all chiller replacements whereas the normalized one depends on the capacity of the selected chiller. In our case, the EnergyPlus software assumes that the chiller has constant COP and auto-sizes the capacity according to peak Summer Design Day. To simplify, we assume that the actual capacity is equal to the peak load. Based on this, the total cost for each chiller retrofit is calculated. Since the lifetime of a chiller is about 15 years and the duration of our life-cycle analysis is 30 years, at the end of the 15th year, we replace again the chiller with another one having the same COP. We include the second capital cost discounted by $(1+i)^{15}$, where i is the discount rate.

For the NPV calculation of each retrofit, we have used a discount rate of 7% and an analysis period of 30 years. In year one, we recognize both a negative cash flow (upfront cost of the retrofit at the beginning of the year) and a positive cash flow (savings recognized at the end of the year). The NPV is calculated for the two electricity price cases of 0.04 \$/kWh which is the current price and 0.09 \$/kWh which is the so-called "cost-reflective" price of electricity as per RSB [18]. It should be noted that a negative abatement cost means that the investment is profitable (has a positive NPV).

In order to develop the MACC we need to calculate the amount of CO_2 abated over a 30-year time horizon. In order to do so, we have to multiply the amount of energy abated (kWh) with the carbon intensity of 1 kWh of electricity. According to the IEA [19], the CO_2 intensity of electricity in the Middle East is approximately 0.65 kgCO_2/kWh. Since the total annual electricity consumption in the Emirate was about 43,251 GWh in 2011 [20] and given that around 84.5% of it is due to the building sector loads, we estimate the total annual electricity load of the building sector in the Emirate to be around 36,547 GWh. Assuming that our typical BAU building accurately represents the average building, we can easily derive the hypothetical number of BAU buildings in the Emirate in order to reach the total load. This number is approximately 5500. It is used below to extrapolate our results to the whole Emirate. The underlying assumption, as mentioned previously, is that the normalized (0–100%) annual load profile of most buildings in Abu Dhabi has the same shape as our BAU building—even though the actual load may vary from building to building. We have established this to be true for the two other building types described in the UPC-Arup report, *i.e.*, the multi-family residential and retail building types. Villas on the other hand present a distinct load profile. Therefore, the results of the present analysis are more pertinent for downtown areas where villas do not constitute a major portion of the load.

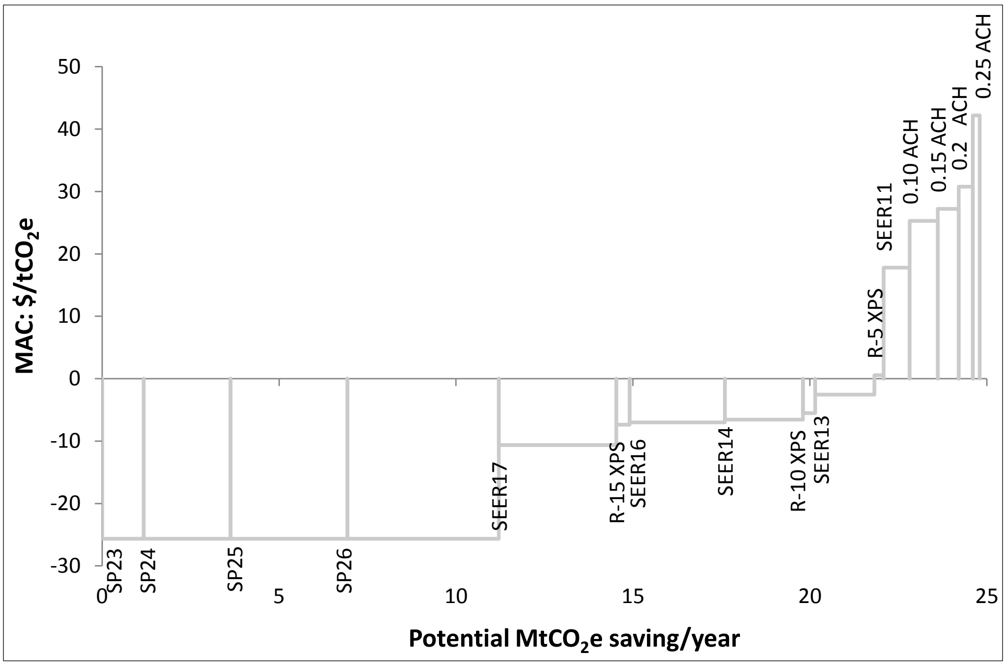
5. Results and Discussion

In the figures below (Figures 6–9), we present the MACC for the emirate of Abu Dhabi for different electricity prices based on the extrapolation of our BAU building.

5.1. Price of Electricity: 0.04 $/kWh

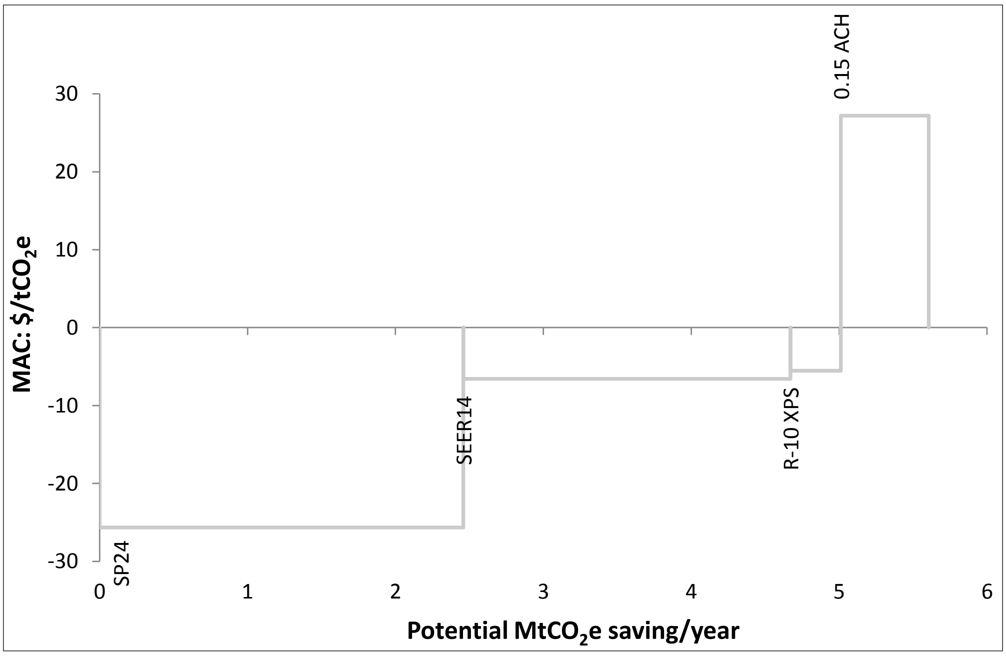
As shown in Figure 6, at this price, many retrofits have a negative NPV. The exceptions are the high efficiency chiller upgrades (SEER14, SEER16 and SEER17) and the high efficiency wall upgrades (R10-XPS and R15-XPS).

Figure 6. The Marginal Abatement Cost Curve (MACC) for electricity price 0.04 $/kWh (ALL levers).



The y-axis shows the cost in US$ per tCO_2 abated whereas the width of each column shows the potential CO_2 abatement per year for each retrofit in $MtCO_2$/a. It is important to note that not all these abatement potentials are cumulative, since we have displayed on the same curve different levels of the same retrofit. In order to have a more conventional MACC, it is important to choose a single level of each retrofit. We have done this based on abatement cost but also based on practical feasibility considerations. For instance, SP24 seems more feasible than SP26 considering that the residents of the Emirate are not yet ready to accept summer set-points enforced in Europe. Similarly, it may be difficult to retrofit a 15 mm layer of wall insulation in existing buildings. Or it may be difficult to drastically improve the air tightness of an existing building which is already relatively air-tight. As for the chiller, it may be difficult to exceed a COP of 3.5 in most practical settings. Therefore, our "feasible" set of retrofits includes SP24, SEER14 (COP = 3.5), R-10 XPS and 0.15 ACH. As shown in Figure 7, only the last retrofit (enhanced air-tightness) does not pay back over the life cycle of the measure.

Figure 7. The MACC for electricity price 0.04 $/kWh (SELECTED levers).



5.2. Price of Electricity: 0.09 $/kWh

In this case, most retrofits have a positive NPV (negative abatement cost) as displayed in the Figures 8 and 9 below. However, minor improvements of air tightness remain unfavorable. Among the selected retrofits group, all four are now self-funding/profitable over the life cycle of the measure.

Figure 8. The MACC for electricity price 0.09 $/kWh (ALL levers).

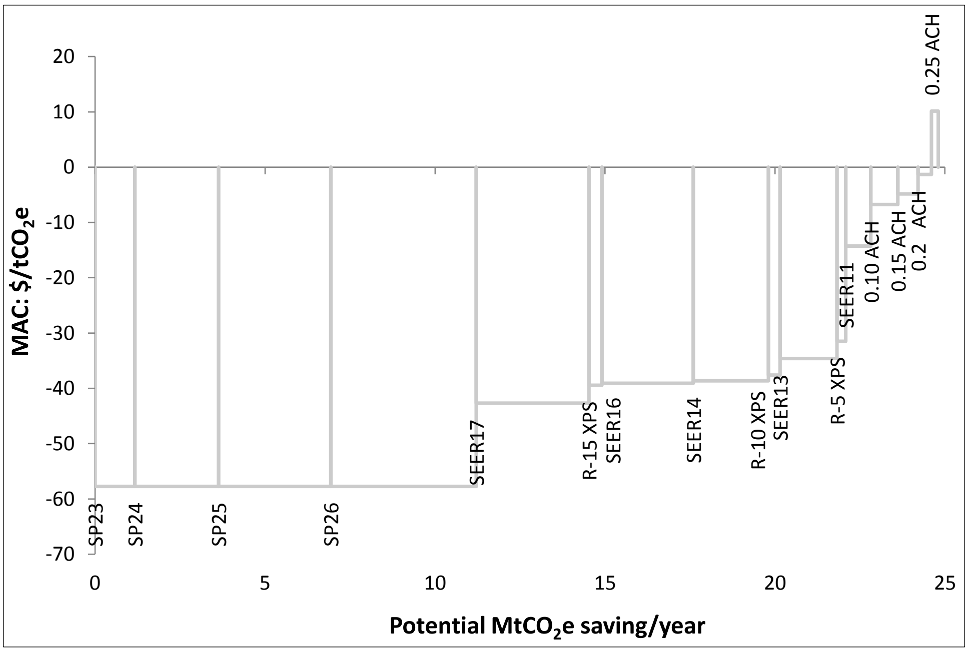
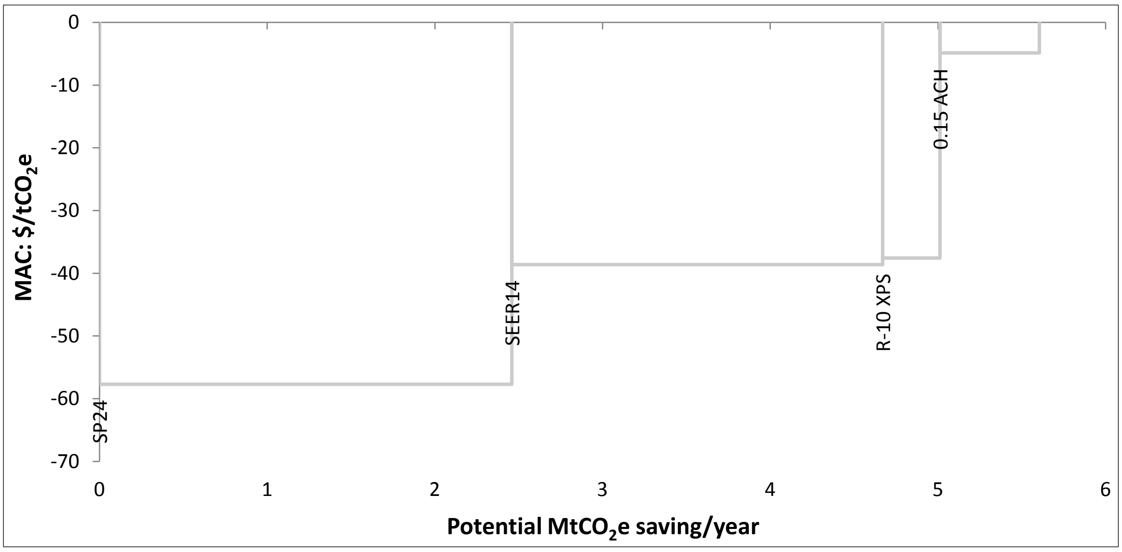


Figure 9. The MACC for electricity price 0.09 $/kWh (SELECTED levers).



6. Conclusions and Future Work

In the current study, we have covered the following items

- Estimation of energy savings in a typical Abu Dhabi building after applying different types of retrofits;
- Extrapolation to the entire building sector of the Emirate;
- Analysis of CO_2 abatement potential;
- Life cycle analysis of retrofit cost and carbon abatement potential;
- Development of a MACC for assessing the impact of AC related demand-side measures in Abu Dhabi.

Based on the above analyses, we have tried to set forth a methodology for the life cycle assessment, at the level of the Emirate, of different building retrofit measures (only retrofits affecting air conditioning have been considered). Although the average building model can be improved—mainly by the addition of other building typologies—and the life-cycle assessment framework can be refined, the methodology is solid and robust. It helps decision makers prioritize among all the possible interventions. It also allows them to predict the impact (energy/carbon) and cost of each intervention over a selected life cycle period. Although we have set the analysis period to 30 years, in line with the estimated life of most retrofits, others may prefer shorter periods based on financial considerations (*i.e.*, bankability). In any case, this tool can be easily adapted to different requirements and specifications.

Our preliminary results comprise a number of lessons. First, unsurprisingly, the zero cost measure consisting in changing cooling temperature set-point by a couple of degrees is extremely effective. This can be achieved via end-user education or through large-scale implementation of appropriate technological solutions (communicating thermostats within a smart grid framework). The importance of chiller efficiency is also emphasized. Despite the upfront cost of replacing a chiller, the NPV of the measure over the life cycle is often positive. Next best is the enhancement of the wall insulation; and finally the improvement of the air-tightness is recommended and can pay for itself if the true (cost-reflective) price of electricity is considered.

Roof enhancement did not add significantly to the performance of the building because of the high number of floors in the BAU building (heat gain through vertical facades more important than through the roof) and the already good quality of the roof. Both of these conditions are unlikely to be met when dealing with other types of buildings, especially villas. So this result will be revisited in future research.

We plan to extend this study by developing other typical building types. We have started working on a villa model for instance. Once we know the approximate ratio and average characteristics of these building types we can extrapolate to the whole Emirate and refine our MACC. We are also thinking of including additional retrofit measures which have an impact on cooling load but cannot be easily modeled using existing commercial building energy simulation software. These include retro-commissioning of the control systems and maintenance of the of the air conditioning equipment. Finally, we intend to develop a numerical model of the heat island and couple it with the typical building model ("co-simulation"). The impact of the urban heat island on the cooling load is significant, and in this region, it is expected to exceed 20% during the summer months.

Author Contributions

Miguel Martin developed the EnergyPlus model of the typical building. Christina Nikolopoulou developed the life-cycle analysis. Afshin Afshari supervised the research.

Conflicts of Interest

The authors declare no conflict of interest.

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