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CLIMATE CHANGE PROGRAMME

SOCIOECONOMIC SYSTEMS: PUBLIC HEALTH BENEFITS OF GHG MITIGATION

- Atmospheric Modelling
- Arabian Gulf Modelling
- Terrestrial Ecosystems
- Marine Ecosystems
- Transboundary Groundwater
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- Public Health Co-Benefits of GHG Mitigation
- Sea Level Rise

Full Technical Report

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AGEDI
مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative

About this Final Technical Report

In October 2013, the Abu Dhabi Global Environmental Data Initiative (AGEDI) launched the "Local, National, and Regional Climate Change (LNRCC) Programme to build upon, expand, and deepen understanding of vulnerability to the impacts of climate change as well as to identify practical adaptive responses at local (Abu Dhabi), national (UAE), and regional (Arabian Peninsula) levels. The design of the Programme was stakeholder-driven, incorporating the perspectives of over 100 local, national, and regional stakeholders in shaping 12 research sub-projects across 5 strategic themes.[1] The "Public Health Co-benefits of Greenhouse Mitigation Activities in Abu Dhabi" sub-project within this Programme aims to assess the impact of past and future policies aimed at reducing greenhouse gas emissions - policies which also have the added benefits of reducing air pollutant emissions - on public health within the Abu Dhabi metropolitan area.

The purpose of this "Final Technical Report" is to offer a summary of what has been learned thus far in carrying out the research activities involved in the "Public Health Co-benefits of Greenhouse Mitigation Activities in Abu Dhabi" sub-project. This report seeks to provide the reader with an overall sense of the methodological approach, analytical framework, data acquisition challenges, key findings, and other issues that can support future policymaking regarding the public health co-benefits regarding the future development and implementation of the Abu Dhabi Climate Change Strategy. Ultimately, this "Final Technical Report" report seeks to provide a useful synthesis of all research activities that offers partners and stakeholders a basis upon which to account for important co-benefits associated with greenhouse gas mitigation strategies.

For more information on the LNRCC programme and the public health co-benefits sub-project, please contact Jane Glavan (jane.glavan@ead.ae).

Table of Contents

List of Tables

List of Figures

List of Boxes

List of Acronyms

ADMA	Abu Dhabi Metropolitan Area
ADNOC	Abu Dhabi National Oil Company
ADWEA	Abu Dhabi Water and Electricity Authority
ADWEC	Abu Dhabi Water and Electricity Company
AF	Attributable fraction
AQM	Air quality model
BIR	Baseline incidence rate
BTEX	benzene, toluene, ethylbenzene and xylenes
CMAQ	Community Multi-Scale Air Quality Model
CO	Carbon monoxide
CoMPA	Co-benefits Mapping Programme – Abu Dhabi
DoT	Department of Transportation of Abu Dhabi
EAD	Environment Agency of Abu Dhabi
EBDA	Environmental Burden of Disease Assessment
EMAL	Emirates Aluminum Company
FAR	Fourth Assessment Report (IPCC)
FIPS	Federal Implementation Planning Standards
GHG	Greenhouse gas
GIS	Geographic Information System
GoAD	Government of Abu Dhabi
HAAD	Health Authority of Abu Dhabi
IARC	International Agency for Research on Cancer
IPCC	Intergovernmental Panel on Climate Change
LNRCCP	Local, National, and Regional Climate Change Programme
NCAR	National Center for Atmospheric Research
NO_x	Nitrogen oxides
O_3	Ozone
OECD	Organization for Economic Co-operation and Development
OSHA	Occupational Safety and Health Administration (US)
PI	Principal Investigator
PM	Particulate matter
PM2.5	Particulate matter less than 2.5 microns in diameter
PM	Particulate matter less than 10 microns in diameter
RCP	Representative Concentration Pathway
RFI	Request for Information
RR	Relative Risk
RT	Research Team
SCAD	Statistics Centre of Abu Dhabi
SCC	Source Classification Code
SMOKE	Sparse Matrix Operator Kernel Emissions (model
SO2	Sulfur dioxide

SOM	Self Organizing Maps
STMP	Surface Transportation Master Plan
TAR	Third Assessment Report (IPCC)
UAE	United Arab Emirates
UCS	Union of Concerned Scientists
UNC	University of North Carolina
UPC	Urban Planning Council of Abu Dhabi
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compounds
WHO	World Health Organization
WRF	Weather Research and Forecasting model

Executive Summary

Carbon dioxide, the principal greenhouse gas, does not pose health risks to the public, per se. However, there are strong linkages between greenhouse gas emissions that contribute to global climate change and air pollution that contributes to adverse local public health impacts. Activities that lead to greenhouse gas emission reduction can also simultaneously lead to air pollutant emissions and subsequently to the avoidance of adverse public health impacts. Such public health "co-benefits" is the subject of this report.

The driving research question was: "Are there significant public health co-benefits in the greater Abu Dhabi City metropolitan area associated with the emirate's Climate Change Strategy?" The study explored this question by developing an estimate of the number of avoided premature deaths and an estimate of the number of avoided excess health-care facility visits due to the comprehensive implementation the Abu Dhabi Climate Change strategy. Building off of the recently completed Environmental Burden of Disease Assessment, the study integrated numerous types of sector-specific data, multiple modeling frameworks, various technology performance information, regional climate change modeling data, spatial data, and a host of other parameters into an analysis tool called – the Co-benefits Mapping Programme – Abu Dhabi (CoMPAD).

CoMPAD was used to analyze 17 policies that are contained in Abu Dhabi's Climate Change Strategy. Each policy was analyzed individually, as well as part of the entire set of policies. The results of the analysis demonstrate that the implementation the combined policies results in significant reductions in emissions of greenhouse gas and air pollutants; significant improvements in air quality within the Abu Dhabi Metropolitan Area, and a large number of avoided health impacts. The magnitude of the public health co-benefits are summarized in Table ES-1.

Table ES-1: Cumulative public health co-benefits from the implementation of 17 GHG mitigation initiatives incorporated in Abu Dhabi's Climate Change Strategy

Pollutant	Health endpoint	Abu Dhabi Metropolitan Area
Particulate matter	Premature deaths	2,869
	Health care facility visits	40,769
Ozone	Premature deaths	313
	Health care facility visits	42,084
Total	Premature deaths	3,219
	Health care facility visits	82,853

Introduction

In March 2014, a final version of Abu Dhabi's Climate Change Strategy (GoAD, 2014; hereafter "Strategy") was submitted for approval. While the UAE has no legal obligation to reduce or limit greenhouse (GHG) gases, the Strategy represents an important basis for the Government of Abu Dhabi to proactively adopt voluntary measures to mitigate (or reduce) anthropogenic (or manmade) GHGs. Among other things, the Strategy identifies sector-specific initiatives to mitigate GHG emissions over the period 2014-2018.

Upon successful implementation, the initiatives in the Strategy will achieve significant GHG emission reductions over time. Most if not all of the initiatives will also achieve significant reductions of air pollutant emissions in the process. Since air pollution from nitrogen oxides, sulfur oxides, volatile organic compounds, carbon monoxide, and particulates has been linked to serious health impacts, any reduction of their concentration in the atmosphere will yield benefits to human health, or "co-benefits" of GHG mitigation.

The aim of this study was to quantify the public health co-benefits of Abu Dhabi's Climate Change Strategy.2 The analysis focuses on the health benefits to be experienced within the Abu Dhabi metropolitan area from implementation of the Strategy. The research builds upon the UAE's Environmental Burden of Disease study (MacDonald Gibson, et al., 2013); incorporates air quality modeling; and integrates a wide range of Abu Dhabi-specific data for key sectors and activities. This information has been codified into an analytical tool called "Co-benefits Mapping Programme – Abu Dhabi", or CoMPAD, which offers a way to evaluate the beneficial public health impacts from exploring alternative targets, technologies, and practices.

Section 2 provides an overview of the context for the study, including a discussion of climate change, the greenhouse gas mitigation context in the Abu Dhabi emirate, the public health context, and the notion of "co-benefits. Section 3 reviews the methodological approach applied in the study and addresses goals/objectives, major analytical steps, modeling framework, among other topics. Section 4 addresses air pollutant emissions modeling and discusses the various sector-specific models that were developed in the study. Section 5 provides an overview of air quality modeling and documents the struggles encountered while also describing the parameterized approach eventually adopted. Section 6 summarizes the health model that was used to calculate the avoided premature deaths and excess health-care facility visits due to the implementation of greenhouse gas mitigation initiatives. Finally,

[2] This Final Technical Report is a summary of methods and overall results. It builds upon previous technical reports prepared as part of the "Public Health Co-benefits of Greenhouse Mitigation Activities in Abu Dhabi" sub-project. These reports include the "Preliminary Findings Report", the "Draft Visualizations Report", and the "Draft Technical Report". The reader is kindly referred to those reports for quantitative details regarding Abu Dhabi-specific assumptions (e.g., population characteristics, transport sector characteristics, power plant locations and characteristics, etc).

Section 7 presents the core conclusions of the study, namely the magnitude of the health co-benefits that can be expected from implementing a comprehensive set of GHG mitigation measures.

1. Background

This section provides an overview of the key issues involved in quantifying public health co-benefits associated with GHG mitigation policies. The section begins with a brief overview of the climate change context, followed by a summary of greenhouse gas mitigation objectives and public health priorities in the Abu Dhabi emirate. The section concludes with a discussion of the concept of the public health "co-benefits" of GHG mitigation strategies.

1.1 Climate context

At the global level, there are clear trends that climate has been changing. Average worldwide surface temperatures have warmed by about 0.74°C over the past century (IPCC, 2007b). Seven of the eight warmest years on record have occurred since 2001. And, within the past 30 years, the rate of warming across the globe has been approximately three times greater than the rate over the last 100 years (USEPA, 2011). In the future, the Intergovernmental Panel on Climate Change (IPCC) projects that global temperatures could rise by between 1.1 and 6.4 degrees Celsius above 1980 - 1999 levels by the end of the 21st century (see Box 1), depending on the levels of future greenhouse gas emissions (IPCC, 2007a).

Box 1-1: Intergovernmental Panel on Climate Change (IPCC, 2011)

WMO and UNEP set up the IPCC in 1988. Its role is to assess on a comprehensive, objective, and transparent basis the scientific, technical and socio-economic information relevant the scientific basis of human-induced climate change, its potential impacts and options for adaptation and mitigation.

The IPCC bases its assessments on peer-reviewed and published scientific literature. It has produced a series of publications which have become standard works of reference. The international community considers that the assessments of the IPCC provide the most authoritative and comprehensive picture of all aspects of climate change.

At the Arabian Peninsula level, there is ample evidence that climate has also been changing. While the region is well-known for its very hot summers and very low annual rainfall, the region has become even hotter over the past 50 years (Zhang, et al, 2005). In essence, the number of days per year that temperatures are above the highest historical (i.e., maximum) levels have been increasing (Figure 2-1, top maps). And, the number of days per year that temperatures are below the lowest historical (i.e., minimum) levels have been decreasing (Figure 2-1, bottom maps). In the future, recently completed studies under the LNRCCP show that the Arabian Gulf countries are expected to be subject to the following by the latter part of the 21st Century. LNRCCP, 2015a; LNRCCP, 2015b). A brief summary is provided in the bullets below.

- *Temperature:* Average future temperature increases will be fairly evenly distributed across the region, on the order of 2° to 3°C higher over land areas and 1.5 to 2 degrees over Gulf waters. Future increases are slightly smaller over many coastal areas. These changes are generally consistent across winter and summer months.

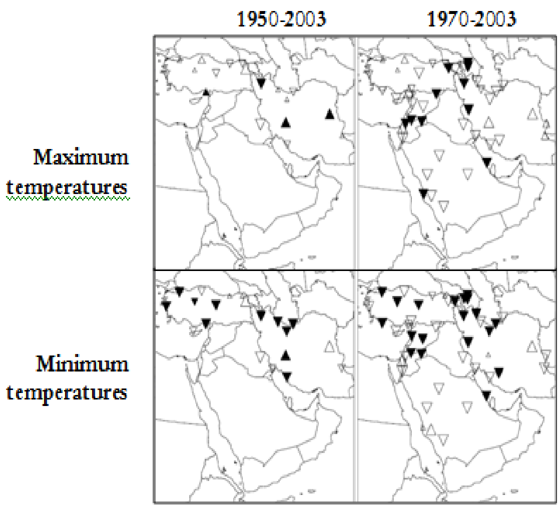
- *Rainfall:* Decreasing rainfall is projected over much of Oman and eastern Saudi Arabia. Projected rainfall increases over the Arabian Gulf and north of the Hajar Mountains primarily occur during winter.
- *Humidity:* Future changes in humidity will increase and be greater in the summer months than in the winter months, with higher humidity across most of the UAE and proportionally more in the northeastern corner associated with greater humidity over the Arabian Sea.
- *Wind.* Wind patterns in the future are projected to change in both magnitude and direction. Under current climate conditions, wind is from the northeast off of the Arabian Gulf during early winter mornings, while in the future, wind from the interior of the UAE will be stronger during early winter mornings resulting in a net change in early morning wind from east to west.
- *Extreme events*. Some intense cyclones that originate in the Arabian Sea, off the west coast of India, are projected to propagate westward towards the Arabian Peninsula. One such future cyclone persists far into the Arabian Peninsula, a remarkable event for the region, suggesting a strengthening of extreme events in the future.
- *Sea surface temperature:* Sea surface temperatures are projected to increase throughout the Gulf, with the areas showing the largest temperature increases relative to present-day - about 2.8°C - located at the Strait of Hormuz and along the coastline of Saudi Arabia and Qatar.
- *Sea surface salinity:* Sea surface salinity changes are projected to both decrease and/or increase, depending on location. Areas showing high salinity increases are located along the UAE coast south of the Northern Emirates, with the largest increases in salinity located in Salwa Dawhat, a bay to the west of Qatar.
- *Sea level rise:* Future sea level rise in the Arabian Gulf remains an open question as only dynamic sea level, the smallest of three contributors to future sea level rise, was able to be modeled in the LNRCCP study on regional ocean modeling (LNRCCP, 2015b). Ongoing improvements to global ocean circulation models in the Coupled Model Intercomparison Experiment Phase 6 (CMIP6) process should be able to better address major contributors to sea level rise, namely global thermal expansion of the ocean and accelerated glaciers melting.

1.2 Greenhouse gas mitigation context

The above projected climatic changes at both the global and regional scales are driven by emissions of greenhouse gases. That is, climate has been changing due to the build-up of greenhouse gases (GHG) in the atmosphere, primarily carbon dioxide, which have been accelerating at rates that far exceed historical patterns from previous centuries. GHGs are emissions associated with modern-day human activities that involve the burning of fossil fuels, industrial processes, waste management, agricultural production, and land use change. These gases are essential for maintaining life on the earth, essentially warming the surface and lower atmosphere by trapping energy before it can be radiated into space. However, the build-up of anthropogenic GHGs is trapping more and more energy resulting in a destabilization of the climate that is evidenced by higher global temperatures and an increasing frequency of extreme weather events.

Figure 1-1: Extreme temperature patterns in the Arabian Gulf region (adapted from Zhang, et al, 2005)

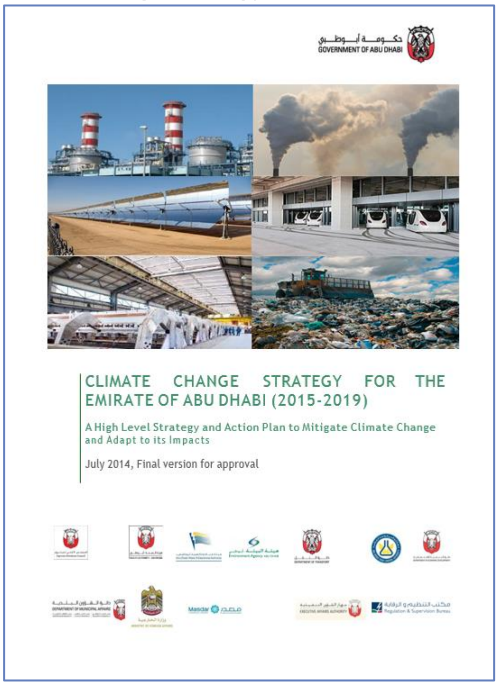
The maps below show trends over the 1950-2003 (left) and 1970-2003 (right) periods for the Arabian Gulf and its vicinity. Upward-pointing triangles indicate increasing trends; downward-pointing triangles indicate decreasing trends. Solid triangles indicate statistical significance. The top figures correspond to the number of days that temperatures are above the highest historical levels - most of the triangles are downward-pointing for 1970-2003 indicating that days of extreme heat are increasing. The bottom figures correspond to the number of days that temperatures are below minimum temperatures - most of the triangles are downward-pointing for 1970-2003 indicating days of cool temperatures are decreasing.



In response, all countries in the Arabian Gulf region have undertaken considerable efforts to address climate change. All of the six countries have signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). All have submitted at least their Initial National Communications under the UNFCCC, with the UAE having submitted its Third National Communications in 2013. All have signed and ratified the Kyoto Protocol that addresses efforts to limit the future growth in greenhouse emissions. In the UAE, GHG emissions are dominated by energy-related activities. GHG emissions were about 174 Tg of carbon dioxide-equivalent (CO2e) in 2005, with energy production and consumption accounting for 88% of these emissions. These levels of GHGs have been increasing steadily in the past decade consistent with the strong socio-economic growth in the country.

Under the UNFCCC, Annex 1 countries are obligated to develop strategies to reduce national GHG emissions consistent with country-specific emission quotas. As a Non-Annex I Party to the UNFCCC, the UAE is not bound by such commitments and therefore has no legal obligation to reduce or limit national GHG emissions. Nevertheless, there is broad consensus at the Abu Dhabi emirate level, as well as for the UAE as a whole, that climate change is a threat to national development aspirations and that voluntary responses that limit the future growth in GHG emissions are essential. In view of this, a Climate Change Strategy has been developed for the emirate of Abu Dhabi under the auspices of numerous stakeholder agencies (see Figure 2-2). Within the Strategy, a set of government priorities, outcomes and targets are outlined requiring actions within all GHG-emitting sectors, namely water and electricity (W&E), Oil and gas, Buildings, Transport, Industry, Waste, and Agriculture.

Figure 1-2: Cover page of Abu Dhabi's Climate Change Strategy (GoAD, 2014)



1.3 Public health context

Carbon dioxide, the principal greenhouse gas, does not pose health risks to the public, per se. However, there are strong linkages between greenhouse gas emissions that contribute to global climate change and air pollution that contributes to adverse local public health impacts. That is, activities that leads to greenhouse gas emissions lead to air pollutant emissions at the same time.

Air pollution leads to a number of adverse impacts on human health (Ostro, 2004; WHO, 2010; Pascal, et al., 2013)**.** Air emissions contribute to a range of diseases, symptoms and conditions that impair the health and quality of life for urban residents throughout the world (Chen, et al., 2013; Fajersztajn, et al., 2013; Stern, et al., 2013; MacDonald Gibson, et al., 2013). Numerous epidemiological studies have reported associations between an increase in daily levels of ozone (O3) and particulate matter (PM), and an increase in the rates of mortality and hospital admissions predominantly related to respiratory and cardiovascular diseases. These short-term effects have been extensively documented (Pascal, et al., 2013). Air pollutants emission levels are a function of many factors such as urban population, economic activity, modes of travel/movement, energy sources of electricity, and the efficiency with which energy is used. An overview of the major types of air pollutants is sumamrized below, together with an overview of their major public health impacts (reprinted from UCS, 2014).[3]

[3] Hazardous air pollutants (or air toxics) also lead to harmful health impacts. These chemical compounds have been linked to birth defects, cancer, and other serious illnesses. The US Environmental Protection Agency regulates 187 major air toxics associated with power supply, transport and industrial activities (USEPA, 2005).

- *Particulate matter (PM).* These particles of soot and metals give smog its murky color. Fine particles — less than one-tenth the diameter of a human hair — pose the most serious threat to human health, as they can penetrate deep into lungs. PM is a direct (primary) pollution *and* a secondary pollution from hydrocarbons, nitrogen oxides, and sulfur dioxides. Diesel exhaust from vehicles is a major contributor to particulate matter pollution.
- *Volatile organic compounds (VOC).* These pollutants react with nitrogen oxides in the presence of sunlight to form ground level ozone, a primary ingredient in smog. Though beneficial in the upper atmosphere, at the ground level this gas irritates the respiratory system, causing coughing, choking, and reduced lung capacity.
- *Nitrogen oxides (NO_x).* These pollutants cause lung irritation and weaken the body's defenses against respiratory infections such as pneumonia and influenza. In addition, they assist in the formation of ground level ozone and particulate matter.
- *Ground-level Ozone (O_3).* Ground-level ozone is not an air pollutant emission per se. It is formed by the emissions of NO_x and VOCs as they react in the presence of sunlight. Ground level ozone is a primary ingredient in smog that reduces visibility in urban areas. At the ground level, this gas irritates the respiratory system, causing coughing, choking, and reduced lung capacity.
- *Carbon monoxide (CO).* This odorless, colorless, and poisonous gas is formed by the combustion of fossil fuels such as gasoline and is emitted primarily from cars and trucks. When inhaled, CO blocks oxygen from the brain, heart, and other vital organs. Fetuses, newborn children, and people with chronic illnesses are especially susceptible to the effects of CO.
- *Sulfur dioxide (SO_2).* Power plants and motor vehicles create this pollutant by burning sulfur-containing fuels, especially diesel. Sulfur dioxide can react in the atmosphere to form fine particles and poses the largest health risk to young children and asthmatics.

The concertation of air pollutants is highly influenced by climatic conditions. Changes in climate affect the concentration of air pollutants in the atmosphere in a number of ways. These include ventilation rates (i.e., wind speed, mixing depth, convection, frontal passages), precipitation scavenging, dry deposition, chemical production and loss rates, natural emissions, and background concentrations (Jacob and Winner, 2009). Each of these climatic factors is projected to change in the Arabian Gulf region, as the results of the LNRCCP's regional atmospheric modeling study showed. Ozone is strongly correlated with temperature (Cox and Chu, 1995), with the hottest summers typically showing the worst air quality.

Addressing air pollution is a key policy priority in Abu Dhabi. The planning priorities and goals of the Health Authority of Abu Dhabi (HAAD) emphasize reducing air pollution to minimize long-term health risks to Abu Dhabi's population. Notably, pollution from power

Four of these monitored by the EAD, namely benzene, toluene, ethylbenzene and xylenes, or the "BTEX" compounds.

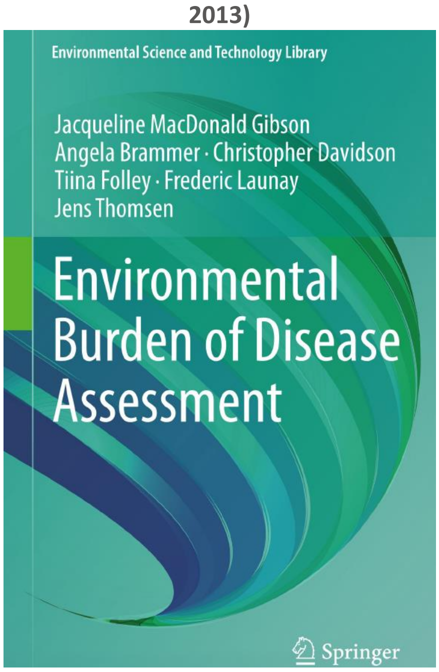
plants, motor vehicles, and industries is implicated as an underlying factor across several of HAAD's public health priorities. Table 2-1 provides a brief summary of how these pollution sources affect public health relative to HAAD's priority areas.[4]

Table 1-1: Public health goals & priorities in Abu Dhabi that intersect with environmental factors (adapted from HAAD, 2014)

Goal	Objective	Environmental factors
Cardiovascular disease prevention and management	Reduce cardiovascular disease burden by preventing the onset of, and improving control and treatment of risk factors for CVD including obesity and overweight, smoking, diabetes, high blood pressure and cholesterol.	Outdoor air pollution, specifically fine particles, can trigger heart attacks and strokes that cause disability and death (e.g., Brook, et al., 2004). Fine particles are emitted year-round from motor vehicles, power plants, and industries
Occupational & environmental health	Reduce incidence of occupational and environmental-related diseases and injuries among the working population in Abu Dhabi Emirate	Poor indoor air quality has been tied to headaches, fatigue, trouble concentrating, and irritation of eyes, nose, throat & lungs (e.g., OSHA, 2011).
Mother, infant and school health	Reduce mortality and morbidity related to pregnancy, childbirth, & postpartum/postnatal periods; and enable school children and adolescents adopt healthy lifestyle behaviours and by creating supportive healthy environments inside schools	Recent studies indicate that air pollution, particularly traffic-related pollution, is associated with infant mortality and the development of asthma, allergies, and acute bronchitis (e.g., WHO, 2005; Schwartz, 2004).
Cancer control and prevention	Reduce the incidence and mortality of cancer by preventing it, if possible, and ensuring early diagnosis and/or treatment	Lung cancer risk increases with increasing air pollution exposure levels, a conclusion that applies especially to fast-developing areas (e.g., IARC, 2013)
Other chronic conditions including Asthma	Improve the health status and quality of life of people living with chronic conditions	Ozone (found in smog) and particulate pollution (found in haze, smoke, and dust) affect asthma. Adults and children with asthma are more likely to have symptoms (USEPA, 2014).

The annual public health impacts associated with outdoor air pollution was estimated in the Abu Dhabi Environmental Burden of Disease Assessment (EBDA). Led by the University of North Carolina, EAD, and HAAD, the research team used local population and local hospital data for the Abu Dhabi emirate to develop a set of relationships between local air pollution and public health (MacDonald Gibson, et al., 2013). Prior to the completion of this study, the only estimates of the links between pollution and health for Abu Dhabi residents were inferred from research in other settings, many with demographic and health conditions different from those prevailing in Abu Dhabi. The results of the research were published in book form in 2013 (see Figure 2-3).

Figure 1-3: Cover page of Abu Dhabi's Environmental Burden of Disease Assessment (MacDonald Gibson, et al., 2013)



The results of the EBDA provide the first locally-derived estimates of the role of environmental factors - namely outdoor and indoor air pollution - on mortality and morbidity risks to the population of Abu Dhabi. Using a measurement-based approach that relied on data from 10 fixed monitoring stations in Abu Dhabi emirate, the EBDA estimated that in 2008 the total number of premature deaths in the UAE caused by exposure to ambient outdoor particulate matter was approximately 650, with an additional premature 77 deaths attributable to outdoor ground-level ozone.

[4] Five of nine priority areas implicate environmental conditions. Other priority areas not directly linked to air pollution include tobacco control, communicable disease prevention and control, road safety, and oral health.

Moreover, the study found that particulate matter in the atmosphere directly led to about 15,000 health-care facility visits for a range of respiratory and cardiac illnesses in 2008, while ground-level ozone led to an additional 9,800 respiratory health-care facility visits in 2008. The EBDA also developed a series of model-based estimates using the Community Multiscale Air Quality (CMAQ) modeling system to predict air quality based on estimates of air pollutant emissions and meteorological conditions.

Table 2-2 provides a summary of health impacts from outdoor air pollution at both the Abu Dhabi emirate and national levels. It is important to note that the EBDA focused on particulate matter and ground level ozone, responsible for a large share of the impacts on human health. Other pollutants that adversely affect public health such as air toxics (e.g., benzene. toluene, ethylbenzene, xylenes, etc) emitted by vehicles or other productive activities that were not considered in the assessment.

Table 1-2: Environmental burden of disease in Abu Dhabi and the UAE from outdoor air pollution (MacDonald Gibson, et al., 2013)

Pollutant	Health endpoint	Abu Dhabi emirate	Rest of the UAE	Total
Particulate matter	Premature deaths	230	420	650
	Health care facility visits	7,700	6,900	14,600
Ozone	Premature deaths	27	50	77

1.4 Co-benefits context

The term "co-benefit" is most often defined in the recent literature as the unintended positive side effect of a policy (Smith, et al., 2008; Ren, et al., 2012; West, et al., 2013). The term has evolved since the early 1990's when it first emerged in policy discussions related to accounting for benefits associated with global climate change and local air quality policies. By the time of the IPCC's Third Assessment Report (TAR), co-benefits were considered the unintended positive side effects of a policy whose aim was at a distinct set of other benefits (IPCC, 2001). Additional terms such as "side benefits", "secondary benefits", "collateral benefits", and "associated benefits" have also been used to connote the same concept.

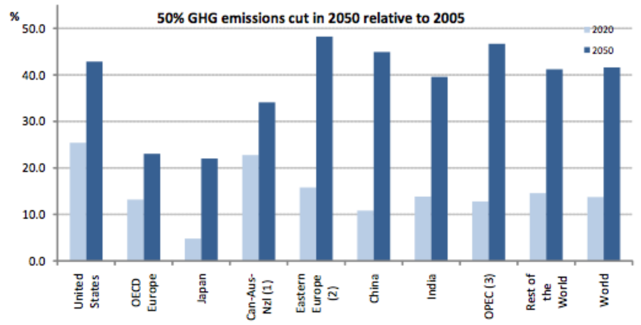
Box 1-2: Defining "co-benefits" (IPCC, 2007; USEPA, 2004)

By the time of the IPCC's 4th Assessment Report (FAR), there was a widespread recognition that co-benefits were any ancillary effect of policies designed to address greenhouse gas mitigation that also achieved other important objectives of development, such as enhancing public heath, improving environmental quality and heightening amenity. The focus eventually came to be on integrated approaches to quantify the co-benefits that could be derived from implementing policy, technology, and infrastructure measures to simultaneously reduce air pollutants and GHG emissions.

Today, the definition of co-benefits has largely coalesced around the use integrated approaches to capture the multiple benefits associated with development objectives (see Box 2-2). For the purposes of this sub-project, the OECD's working definition of a co-benefit is being used, namely any "*potentially large and diverse range of collateral benefits that can be associated with climate change mitigation policies in addition to the direct avoided climate impact benefits*" (Bollen, et al., 2005).

There are many types of GHG mitigation policies that can lead to public health co-benefits. Specifically, energy efficiency, renewable energy and nuclear power imply a diverse range of co-benefits, including improvement in public health (IPCC, 2007). Moreover, while reducing energy-related GHG emissions yields a global impact, co-benefits are experienced either locally or at the regional level. This is particularly true regarding the public health co-benefits associated with GHG mitigation where studies have shown sharp reductions in morbidity and mortality risks associated with aggressive GHG reduction policies (Bollen, et al., 2009b). For example, the estimated reduction in global premature deaths from reduced air pollutant emissions accompanying GHG mitigation strategies would approach 50% in 2050 relative to 2005 levels (see Figure 2-4).

Figure 1-4: Avoided premature deaths from reduced local air pollution through GHG mitigation policies, % differences from baseline (Bollen, *et al.*, 2009b)



Finally, the co-benefits of GHG mitigation represent potentially useful decision criteria for policymakers, but are often neglected (Jochem and Madlener, 2003; IPCC, 2007). There are many cases where the net co-benefits of particular GHG-reducing strategies have not been identified for decision-makers and businesses. Since due consideration of co-benefits has the potential of influencing policy decisions concerning the implementation of GHG mitigation initiative, it is important to consider co-benefits at the earliest scoping stages. This is a strategic consideration as most co-benefits produce short-term effects, and can therefore support a vital link to the longer-term benefits associated with GHG mitigation policies (Kessels and Bakker, 2005). Recent studies indicate that this situation is changing, with studies underway to capture the magnitude of the co-benefits associated with GHG mitigation options (Creutzig and Dongquan, 2008; Smith, K. and Haigler, 2008; WHO, 2011).

2. Methodology

This section provides an overview of the methodological approach for quantifying public health co-benefits associated with GHG mitigation strategies. The section begins with a brief overview of the core research question underlying the study. This is followed by a summary of the study's goals/objectives, conceptual approach, key analytical steps, and modeling framework. The section concludes with a discussion of the approach adopted for making accessible an ability by interested stakeholders to conduct public health co-benefits analysis.

2.1 Core research question

Are there significant public health co-benefits in the greater Abu Dhabi City metropolitan area associated with the emirate's Climate Change Strategy? This is the core research question underlying the methodological approach. That is, can a reliable estimate be developed regarding the number of avoided premature deaths and the number of avoided excess health-care facility visits due to the implementation the Abu Dhabi Climate Change strategy, in part or in whole? As discussed in the subsections that follow, addressing this question has involved extensive local data acquisition and focused on a number of interlinked issues such as regional climate change modeling, air pollutant emission inventory development, air quality modeling, demographic characterizations, and epidemiological research.

2.2 Goals and objectives

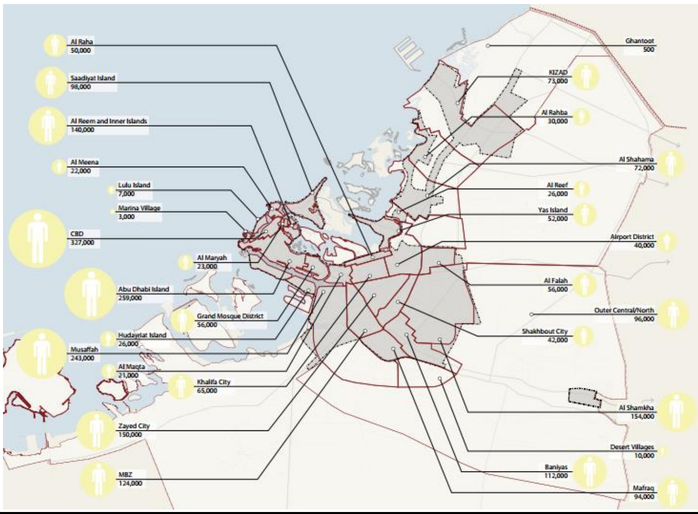
The overall goal of the sub-project is to better understand the public health implications Abu Dhabi's Climate Change Strategy, individually and collectively, at the metropolitan spatial scale. This involves a quantification of the public health response with and without GHG mitigation initiatives, as well as understanding the public health response under changing climatic conditions. There are five major objectives, as outlined in the following bullets.

- *Characterize population.* Establish current and future baseline population characteristics in the Abu Dhabi Metropolitan Area. This involves the development of a database that incorporates information on the qualities and characteristics of various types of populations with emphasis on demography, health status, and socioeconomic factors.
- *Characterize current and future climate.* Establish current and future meteorological conditions in the Abu Dhabi Metropolitan Area. This involves accessing a subset of the detailed outputs of the Weather Research and Forecasting (WRF) model used in LNRCC sub-project #1 (Regional Atmospheric Modeling) to establish current and projected climatic conditions.
- *Identify bad air quality days.* Reduce the dimensionality of the extensive meteorological dataset record produced by the WRF simulations through the use of the Self Organizing Maps (SOM) methodology. This significantly reduces the subsequent computational

requirements in subsequent modeling and makes possible the analysis of additional policies/sensitivities.

- *Estimate local air pollutant emissions.* Characterize the pollutant emissions of specific sectors where GHG mitigation activities are underway or planned. This involves the development of annual air pollutant emission inventories for the power supply, transport and industrial sectors using locally obtained data.
- *Conduct air quality modeling.* Undertake a parameterized approach to air quality modeling to determine the changes in ambient air concentration of air pollutants and air toxics associated with the implementation of GHG mitigation initiatives. This involves first converting annual emission inventory data to the temporal, spatial, and pollutant species resolution needed by the air quality model and then running an air quality model accounting for climate change.
- *Estimate public health co-benefits.* Quantify public health co-benefits associated with GHG mitigation activities. This involves the application of locally-derived concentration-response functions to convert the change in ambient air pollution concentrations from the implementation of GHG mitigation strategies into estimates of corresponding public health co-benefits.
- *Develop a co-benefits mapping software program.* Synthesize all inputs and outputs into a user-friendly tool. Such a tool is intended to codify the methodology and assumptions of the above activities in order to enhance the transparency of the analysis and to provide a way for stakeholders and partners to explore public health co-benefits of additional policies and strategies.

Figure 2-1: Spatial domain of the study - Abu Dhabi Metropolitan Area (source: Plan Capital 2030; Figure 3.1, October 2014)



2.3 Foundational aspects

There were three aspects that were foundational to the methodology applied in the study. First, a "bottom-up" methodology was used to assess the public health co-benefits of GHG mitigation activities. The term "bottom-up" refers to one of two different approaches to examine the linkages between specific pollutant-emitting sectors and the impacts on the environment (or public health) that they produce. A bottom-up approach relies heavily on local data to define emission sources/trends, demographic characteristics, health conditions of sub-populations, and actual types of technologies either currently used or planned. Bottom-up approaches to energy/environment modeling are able capture the needed details and complexity of emissions and their atmospheric dispersion within a local/regional context. They are distinguished from "top-down" approaches, which rely almost exclusively on a set of aggregate indicators to represent current and planned conditions. Given the importance of being able to show a high degree of health benefit granularity, the bottom-up approach was applied.

Second, the greater Abu Dhabi metropolitan area was used as the study domain for which public health co-benefits were estimated. This is a region of approximately 3,800 square kilometers, and is shown in Figure 3-1. The Figure also shows assumptions regarding population per precinct in the year 2030. The area includes current high population density areas of about 1,030 people/km^2 within Abu Dhabi Island (as compared to 36 people/km^2 for the entire emirate); it also includes surrounding areas where urban expansion plans call for significant future residential and industrial zones to the south and east. These are the very areas that are expected to bear the brunt of increased air pollution under a Business-as-usual scenario and would benefit the most from the implementation of Abu Dhabi's Climate Change Strategy.

Third, the Abu Dhabi Climate Change Strategy (GoAD, 2014) was used as the policy domain for which public health co-benefits were estimated. These policies within this strategy document affect several key GHG-emitting sectors, namely power supply, transport, and industry. Within the overall Climate Change Strategy, the focus for health co-benefit analysis was on two specific priorities that were considered to have the most impact on the future growth of GHG emissions in the Abu Dhabi emirate, as described in the bullets below.

- *Priority #2: Clean Energy and Climate Action.* Achieving this priority focuses on policies to accelerate the adoption of low carbon fuels, technologies, practices and processes by utilities (across generation, transmission and distribution.
- *Priority #3: Green Lifestyles and sustainable use of resources.* Achieving this priority focuses on policies to accelerate the adoption of low carbon fuels, technologies, practices and processes by end-user sectors (residential and commercial buildings, transportation and industry.

Specifically, there are 17 specific strategies were chosen for public health co-benefit analysis, as indicated in Table 3-1. Each of these policies have been put forward in the Climate Change Strategy as an effective means of achieving GHG emission reductions. It is important to note that these strategies will also achieve substantial air pollutant emission reductions as a co-benefit. Some, but not all, of these policies are fully described within Abu Dhabi's Climate Change Strategy relative to the particular targets they are designed to achieve. An example of a strategy with clear targets is Policy #9: Demand side management strategies for electricity and water production, which is designed to achieve a 26% reduction in per capita electricity demand per capita by 2030 relative to 2010. An example of a strategy without clear targets at this time is Policy #16: Energy efficiency at industrial cogeneration facilities, where targets are "TBD" within the Climate Change strategy meaning they are still to be determined. For such policies, placeholder targets have been provisionally developed and analyzed.

2.4 Conceptual approach

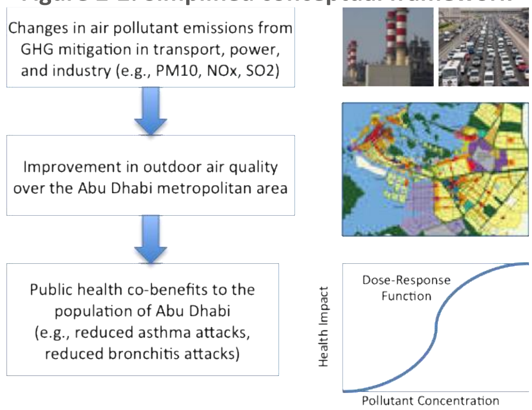
The implementation of a bottom-up approach implied the need to quantify key elements in the sequence from emission reductions to public health co-benefits. Figure 3-2 provides an overview of this sequence. The conceptual approach involved first characterizing the air pollutant emissions with and without the implementation of GHG mitigation policies. Changes in air quality were then computed as the difference in ambient air pollutant concentrations with and without the GHG mitigation policies. Finally, these changes are translated into public health co-benefits through the application of the health model developed as part of the Abu

Table 2-1: Specific policies considered in the assessment of public health co-benefits in the Abu Dhabi Metropolitan Area

Priority	Sector	Programme	Policy No	Description
Clean Energy and Climate Action	Power and water supply	Peaceful nuclear power	1	Nuclear power generation
		Promote renewable energy electricity generation	2	Renewable energy power plants
			3	One renewable energy water desalination pilot project
			4	Renewable energy water desalination plants
			5	Waste-to-energy power plants
			6	Feed in tariff to sell power to the grid
			7	Solar roofs
		Increase power plant efficiency	8	Supply side energy efficiency strategy for electricity and water production
Green Life Styles and Sustainable Use of Resources	Power and water demand	Energy efficiency	9	Demand side management strategies for electricity and water production
		Green buildings	10	Current Estidama initiative
			11	More stringent building codes for energy conservation
			12	Energy efficiency standardization and labeling programme
	Transport	Sustainable transport	13	Transportation demand strategies
			14	Encourage purchase of high efficiency vehicles
	Industry	Energy and industrial efficiency	15	Gas flaring reduction in oil and gas industry
			16	Energy efficiency at industrial cogeneration facilities
			17	Energy efficiency in aluminum production

Dhabi EBDA to the changes in air quality achieved by the greenhouse gas mitigation strategies.[5]

Figure 2-2: Simplified conceptual framework

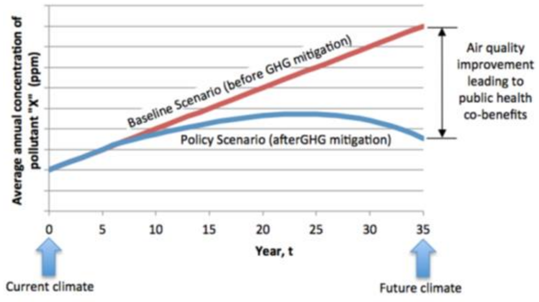


Implied in the estimation of air quality changes is the notion of "scenarios". A scenario is simply a representation of a plausible future under certain conditions. It is not a prediction of the future, but rather a narrative concerning a potential future given certain assumptions. Specifically, two scenarios were considered; a "Baseline Scenario", corresponding to a future where Abu Dhabi's Climate Change Strategy is not implemented and a "Policy Scenario" corresponding to a future where Abu Dhabi's Climate Change Strategy is implemented in part or in whole. Each considered a planning horizon with a 2007 Base Year and a 2035 End Year. The use of a scenario framework over this time period helped to define potential outcomes that would be both relevant to policymakers and plausible for analysis purposes.

An idealized representation of the scenario logic underlying the analysis is provided in Figure 3-3. Absent any initiatives to reduce greenhouse gas or air pollutant emissions, the concentration of air pollutants in the Abu Dhabi Metropolitan Area will continue to increase over the planning period (red line in Figure 3-3). With the implementation of greenhouse gas mitigation initiatives, the concentration of air pollutants in the Abu Dhabi Metropolitan Area will decrease over the planning period, a direct co-benefit of those initiatives (blue line in Figure 3-3).

The curves in Figure 3-3 represent alternative futures regarding air pollution in the Abu Dhabi Metropolitan Area. The "Baseline scenario" curve incorporates long-range pollutant transport, socioeconomic growth and changing meteorological conditions assuming no investments in GHG mitigation. The "Policy scenario" curve also incorporates long-range pollutant transport, socioeconomic growth, changing meteorological conditions, together with the impact of the GHG mitigation measures in Abu Dhabi. The difference in average annual pollutant concentrations between these two curves in each year, when incorporated into the health model from the EBDA, provides an indication of annual public health co-benefits associated with GHG mitigation. When summed

Figure 2-3: Idealized representation of the scenario approach



[5] While not within the scope of this sub-project, the resulting public health co-benefits could then be translated into monetary terms through the application of willingness to pay estimates.

across all years and all grid cells, they provide an indication of the cumulative impact on public health associated with individual or collective GHG mitigation measures.

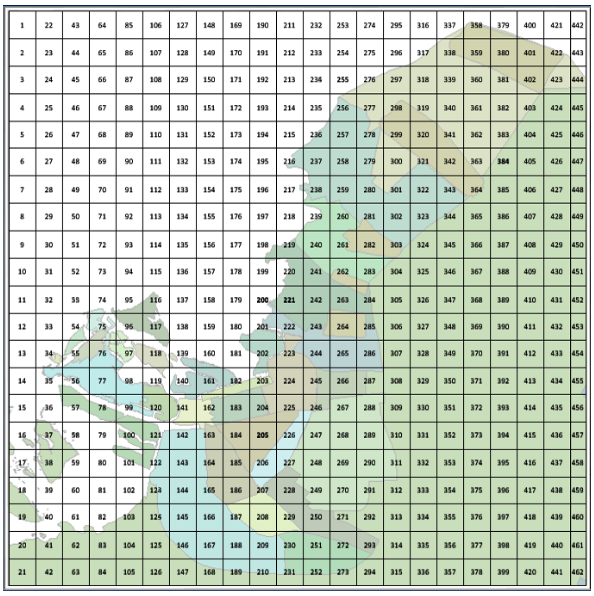
A core assumption concerned the way global climate change would unfold in the spatial domain. For the year 2007, it was assumed that historical climatic patterns would prevail. For 2035, it was assumed that temperature, wind and other climatic parameters resulting from global GHG emissions projected under Representative Concentration Pathway 8.5 (RCP4.5) would be most appropriate. This is the RCP was assumes that global trajectory of GHG emissions would continue similar to past trends. Both the Baseline and Policy Scenarios assumed climate changed conditions in the end year of the planning horizon, 2035. The magnitude of the climate parameters within the Abu Dhabi Metropolitan Area were obtained from the outputs of Domain "D3" of the LNRCCP's regional atmospheric modeling study.

2.5 Key analytical steps

The estimation of public health co-benefits is essentially a quantitative analysis that relies heavily on local data and numerical modeling techniques. Quantification involved the modeling of the linkages between air pollutant emissions, air quality, and public health at the municipal level in the context of plausible scenarios for the implementation of Abu Dhabi's Climate Change Strategy. The sequence of calculations involves a seven (7) major analytical steps, each of which is briefly summarized in the bullets below.

- *Step 1: Establish land area and population characteristics in the Abu Dhabi Metropolitan Area.* An essential starting point was to divide the Abu Dhabi Metropolitan area into 4 km by 4 km grid cells. This gridded spatial domain made it possible to provide estimates of air quality changes and public health co-benefits at a high spatial resolution. A total of 462 grid cell make up the metropolitan plus offshore area, as illustrated in Figure 3-4. Demographic characteristics for the 28-year period from 2007 through 2035 (e.g., population by precinct, population by age group) were then apportioned to each cell.

Figure 2-4: Gridded spatial domain of the study area



- *Step 2: Establish current and future climatic conditions***.** Each grid cell in the gridded area was characterized by a set of climatic characteristics. Establishing current and future climatic conditions in the Abu Dhabi Metropolitan Area relied exclusively on the outputs of the LNRCCP's regional atmospheric modeling sub-project which applied the Weather Research and Forecasting (WRF) model to generate average daily, monthly, and annual climatic conditions regarding temperature, wind speed, rainfall, humidity, solar insolation and numerous other meteorological parameters for 2007 and 2035 for each 4 km by 4 km grid cell within the Abu Dhabi Metropolitan Area. The ultimate aim of establishing current and future climatic conditions at this spatial resolution was to be able to adequately represent specific meteorological conditions that influence the formation of pollutants in the atmosphere.

- *Step 3: Reduce dataset dimensionality to identify bad air quality days.* The regional climatic data was analyzed within the context of the model-based CMAQ outputs from the EBDA to identify particularly bad air quality days. This kind of information was developed in order to inform subsequent analyses for information only. In so doing, the key aim was to reduce the dimensionality of the extensive meteorological dataset record produced by the WRF simulations. The size of the WRF meteorological dataset totals over 55 million pieces of data Reducing dimensionality means to collapse the size of the dataset while still capturing essential trends and patterns. The Self Organizing Map (SOM) methodology was used to reduce the dimensionality of the WRF and CMAQ data outputs. Essentially, the SOM methodology involves pattern recognition or data classification through a learning process; with the result being a projection of high-dimensional input data onto a low dimensional space which significantly reduces the size of the data set and subsequent computational requirements in modeling, making possible the rapid analysis of policies and sensitivities.
- *Step 4: Compute air emission impacts associated with each initiative in Abu Dhabi's Climate Change Strategy.* Annual air emissions in the Abu Dhabi Metropolitan Area were estimated through the integration of the three emission models, namely power supply, transport, and industrial emissions models. Each of these models was developed using standard practice energy-environment analysis methods. Each model was populated with a variety of technology, behavioral, growth, pollution controls, and other assumptions from official government sources under Business-as-Usual conditions in an effort to customize the analysis to the unique conditions of the Abu Dhabi Metropolitan Area. The emission models combined historical activity data regarding sector-specific parameters (e.g., annual net electricity generation), with technology-specific assumptions (e.g., nitrogen oxide emission factors for cars by vintage), with future expansion/growth assumptions (e.g., forecasted oil production at offshore facilities) to produce an emissions projection for air pollutants and GHGs for stationary and mobile sources over the entire planning period.
- *Step 5: Conduct parameterized air quality modeling.* The resulting annual emissions of air pollutants represent inputs to air quality modeling. Originally, this was planned to be undertaken in a two-step process in which annual emission outputs from the previous step would be pre-processed in the Sparse Matrix Operator Kernel Emissions (SMOKE) model to format emissions so that they would be consistent with the temporal, spatial, and pollutant species resolution formats needed by CMAQ, the air quality model to be used. Due to difficulties in getting SMOKE to run, this initial approach was replaced late in the study by a parameterized version of air quality modeling. Essentially, the outputs of the 2007 CMAQ run undertaken as part of the EBDA were used as a basis by which to predict air quality in each grid cell for 2007; for each grid cell in 2035 under the Baseline Scenario; and for each

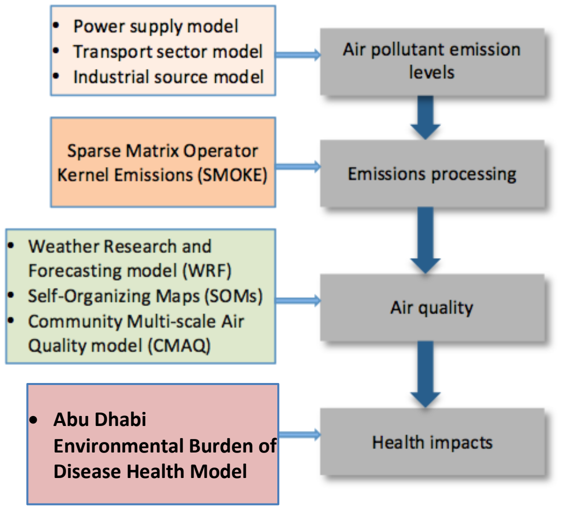
grid cell in 2035 for a Scenario that reflected the emission impact from the implementation of all 17 policies in Abu Dhabi's Climate Change Strategy.

- *Step 6: Estimate the temporal change in air quality associated with Abu Dhabi's Climate Change Strategy.* Annual estimates of air quality between the start year of a policy and 2035 were estimated through the application of numerical techniques. This was necessary because the parameterized approach to air quality modeling provided estimates of pollutant concentrations at the temporal endpoints, i.e., 2007 and 2035 only. That is, air quality modeling generated concentrations of NOx, VOCs, O3, PM2.5, PM-10, CO, and SOx for the Base Year (2007) and for the end year of the planning period (i.e., 2035) under the Baseline and (All) Policy Scenarios. However, in order to capture the temporal nature of the impact of individual initiatives, a further parameterization process involving interpolation was carried out to account for the start year of the initiative, its rate of implementation, and the level of emission reductions achieved.
- *Step 7: Calculate public health co-benefits.* The final step in the analytical sequence was to translate changes in ambient air pollution concentration associated with GHG mitigation to public health co-benefits within the Abu Dhabi Metropolitan Area. The scope of public health benefits was defined by the specific air quality-related public health categories described in the Abu Dhabi Environmental Burden of Disease Assessment. These categories focus on a range of adverse health impacts associated with ambient air concentration of particulate matter (which include sulfates) and ozone (which is formed from emissions of nitrogen oxides and volatile organic compounds). The improvement in air quality, as determined in the previous steps, was incorporated into the health model and aggregated over the total grid cells to estimate the total number of premature deaths avoided and the excess health-care facility visits avoided per individual or combination of GHG mitigation initiatives.

2.6 Modeling framework

The sequence of calculations from emissions to health co-benefits required the development of a comprehensive modeling framework. An idealized representation of the components and analytical flow sequence within CoMPAD appears in Figure 3-5. The paragraphs that follow provide an overview of each element of the modeling framework.

Figure 2-5: Idealized representation of the CoMPAD modeling framework



At the outset, it is important to note that underlying the modeling framework is local data. Specifically, seven key datasets were assembled including population characteristics, a vehicle inventory, a power plant inventory, an industrial facility inventory, climate data, air quality data, and epidemiological data (i.e., health model developed by the EBDA). Default data assumptions across these categories are provided in the CoMPAD tool.

Three emissions models were developed to forecast GHG and air pollutant emissions. The resulting annual air emission levels associated with these forecasts represent the environment loadings to the atmosphere, which then serve as inputs for subsequent air quality modeling efforts. An overview of each planning model is provided in the paragraphs below, with additional details provided later in this report.

- *Power supply model* forecasts electricity and desalinated water production consistent with projected socio-economic growth within the Abu Dhabi Emirate. It includes all capacity, generation, and electricity transmission components that together comprise ADWEA operations. The model quantifies air pollutant and GHG emissions by power plant site over the period 2007 through 2035 for the Baseline and each policy in the Policy Scenario.
- *Transport model* forecasts travel patterns consistent with projected public transport and road infrastructure expansion. It codifies and integrates assumptions embedded in the travel demand model developed by the Department of Transportation for Abu Dhabi's Surface Transportation Master Plan (DoT, 2009, 2013) and its updates. The model quantifies air pollutant and GHG emissions by vehicle type over the period 2007 through 2035 for the Baseline and each policy in the Policy Scenario.
- *Industrial model* forecasts industrial productivity consistent with long-range plans. As a simplifying assumption, the focus of the industrial model is on four distinct activities, aluminum production, offshore oil operations, oil refining, and onsite production of process heat and electricity. Together, these activities represent a large share of air emissions associated with industrial activities.

Several models played a role during the course of the study in efforts to forecast changes in ambient air concentration of air pollutants under changing climatic conditions. The resulting air pollutant concentrations associated with these forecasts represent the impact of emissions to the atmosphere, which then serve as inputs for subsequent health modeling efforts. An overview of each model is provided in the paragraphs below, with additional details provided later in this report.

- *Weather Research and Forecasting (WRF) model.* This is the model that was used to develop estimates of climatic changes (e.g., temperature, precipitation, relative humidity, wind) under climate change conditions at the regional scale due to increasing concentrations of greenhouse gases (GHG) in the atmosphere. The model was run previously in a separate study (LNRCCP, 2015a). Its outputs were incorporated into the current study.
- *Self Organizing Maps (SOM) model:* This is a modeling approach that was used to reduce the dimensionality of the extensive meteorological dataset record produced by the WRF simulations for the time slice periods, as well as the Community Multi-scale Air Quality model (CMAQ) modeling outputs for the Base Year of 2007. It was used during initial explorations to evaluate how meteorology, emissions, and air chemistry data influence air quality in the Abu Dhabi metropolitan area. The result of using the model identified the

typical days during the year when air quality is at its worst. The model was run for information purposes only.

- *Sparse Matrix Operator Kernel Emissions (SMOKE) model.* Considerable effort was spent in trying to run this model. Essentially, the model converts the annual source emissions to the temporal, spatial, and pollutant species resolution needed by the air quality model. The original intent was to run SMOKE to process local emissions in the Abu Dhabi Metropolitan Area. However, as discussed in later in this report, it was impossible to get SMOKE to run properly and alternative solutions were developed.
- *Community Multi-scale Air Quality model (CMAQ) model.* This is the model that was used to develop the modeling-based estimates of air quality in the UAE's Environmental Burden of Disease study. At that time, it was run for a period of four summer months in 2007 (i.e., 1 May through 31 August) and 3 winter months in 2008 (i.e., 1 January through 31 March). The original intent was to run CMAQ using the SMOKE-processed local emissions for the Abu Dhabi Metropolitan Area. However, as discussed later in this report, it was impossible to get SMOKE and CMAQ to run properly and a parameterized approach to air quality modeling was used.

Finally, a single health model was used to convert changes in air quality to public health co-benefits. The UAE Environmental Burden of Disease Model was the sole model used evaluate premature avoided deaths avoided and excess health-care visits avoided by the introduction on one or more of the policies in Abu Dhabi's Climate Change Strategy. This is the model developed for Abu Dhabi for the quantification of the public health impacts from the inhalation of outdoor particulate matter and ground-level ozone. The model is described in detail in Macdonald Gibson, et al (2013).

2.7 Public health co-benefit analysis accessibility

Achieving the last objective of the study involved the development of a co-benefits mapping software program. This was carried out in order to make accessible both the actual results of public health co-benefits analysis, as well as offer the capability to interested stakeholders to conduct subsequent analyses. To this end, a model was developed – the Co-benefits Mapping Programme – Abu Dhabi (CoMPAD) – codifying all the data assumptions, modeling techniques, and mapping protocols. The tool is essentially a macro-driven Graphical User Interface (GUI) built in Excel software that uses the modeling framework described in the previous section to implement the sequence of analytical steps described earlier. These steps convert changes in GHG emissions to changes in air pollutant emissions, to changes in air pollutant concentrations to reduced human exposure to air pollution. Using a spatial framework that disaggregates emission reduction impacts by location within the Abu Dhabi Metropolitan Area, CoMPAD provides a flexibility for exploring alternative policy targets, technology characteristics, population growth trends, travel behavior and many other factors and assumptions.

There were five (5) specific aims embodied in the design of CoMPAD. These aims have been established in response to feedback received from stakeholders and partners. They are being reflected during the model design process in order to ensure, as much as possible, that the model's visual and substantive designs are closely aligned with priority concerns of policymakers and decision makers. A description of each aim is provided in the bullets below.

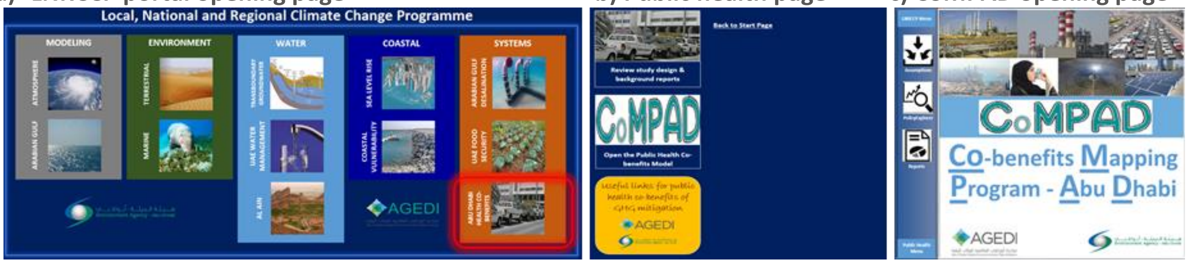
- *Consistency:* This aim seeks to ensure that the model is designed to be consistent with the methodological approach, assumptions, and analytical steps documented in this Technical Report.
- *User-friendliness:* This aim seeks to ensure that the model is intuitive, easy to navigate, and useful to experts for use in research as well as to policymakers for exploring implications of specific policy options.
- *Transparency:* This aim seeks to ensure that the internal databases of the model are readily accessible for review and/or updating by the user. This offers the opportunity for a user to adjust the range of assumptions for the Abu Dhabi metropolitan area (ADMA), as well as adapting the model databases to other metropolitan areas in the Arabian Gulf region.
- *Flexibility:* This aim seeks to ensure that the model offers the capability to explore impacts associated with the implementation of individual greenhouse gas mitigation policies, as well as impacts associated with the simultaneous implementation of all policies. Impacts are offered in graphical, tabular and spatial formats.
- *Focused:* This aim seeks to ensure that model outputs are focused on the impact of specific GHG mitigation policy(ies) already at advanced stages of policy dialogue for upcoming implementation within the emirate of Abu Dhabi. Three key attributes are considered for each policy and the combination of all policies: namely emission reductions, changes in air quality, and avoided public health impacts.

Eventually, CoMPAD will be incorporated into the web-based LNRCCP portal that will contain all visualization tools developed for the 12 studies in the programme. The initial screen seen by the user upon accessing the LNRCCP portal website is shown in Figure 3-6a. Clicking on the public health sub-project icon under the “Systems” strategic theme (lower right icon encircled in red) opens the page in Figure 3-6b, which offers options to either review background documents (top icon), run CoMPAD (middle icon), review useful links (bottom icon), or return to the LNRCCP opening page (white hyperlink). Clicking on the CoMPAD middle icon opens the page shown in Figure 3-6c. The plan is for users to be able to run CoMPAD directly from the web or alternatively, download the model to a PC and conduct runs locally.

CoMPAD's main menu consists of three options. These are indicated in Figure 3-6c by the three icons in the left frame. Clicking on the top icon (Assumptions) provides entry to a series of pages where users can review default assumptions or replace those assumptions with those that are more appropriate or up-to-date. Clicking on the middle icon (PolicyExplorer) provides entry to a series of pages where users can explore the public health co-benefit impact of changing targets (i.e., the ambitiousness of policy implementation) within the framework of Abu Dhabi's Climate Change Strategy. Clicking on the bottom icon (Reports) provides access to a series of reports that document the assumptions underlying a particular CoMPAD run. The tool has been designed to be highly intuitive for navigation. An overview of the model structure and functionality is provided in the Draft Visualizations Report (CCRGb, 2015).

Figure 2-6: Components of the LNRCCP portal for the public health co-benefits study

a) LNRCCP portal opening page **b) Public health page** **c) CoMPAD opening page**



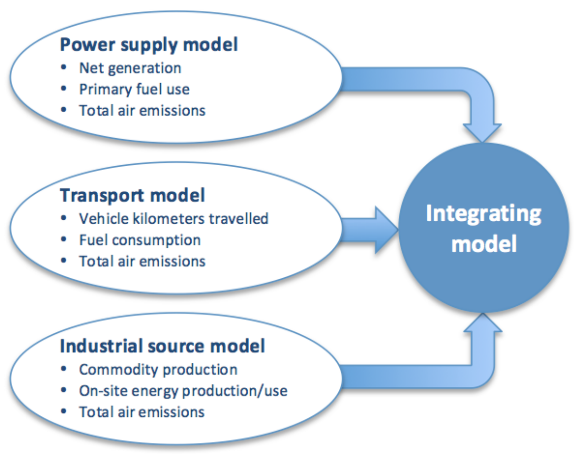
3. Emissions modeling

This section provides an overview of the emissions modeling approach used to estimate greenhouse emission and air pollutant emission reductions from the implementation of one or more of the policies in Abu Dhabi's Climate Change Strategy. The section begins with a brief overview of the overall approach. This is followed by a discussion of each of the emissions models developed in the study.

3.1 Introductory remarks

Annual air emissions in the Abu Dhabi Metropolitan Area were estimated through the integration of three emission models developed in this sub-project. As mentioned earlier, these are the power supply, transport, and industrial models. Each of these models were developed as independent analysis modules that can be run individually to analyze one or more sector-specific policies, or as part of an integrated system to analyze one or more policies across one or more sectors. This modularity implies a system of self-contained parameters, functions, assumptions, and methods. This approach is generally consistent with the analysis of energy-environment linkages, which can be represented by various supply, conversion, and demand components that are largely distinct from one another. Moreover, the modularity of this approach offers the flexibility for each emissions model to be capable of policy-specific analysis of air emission reductions. An idealized representation of the overall modeling system is shown in Figure 4-1. An overview of each emissions model is provided in the subsections below.

Figure 3-1: Idealized representation of overall modeling system to estimate air emission impacts

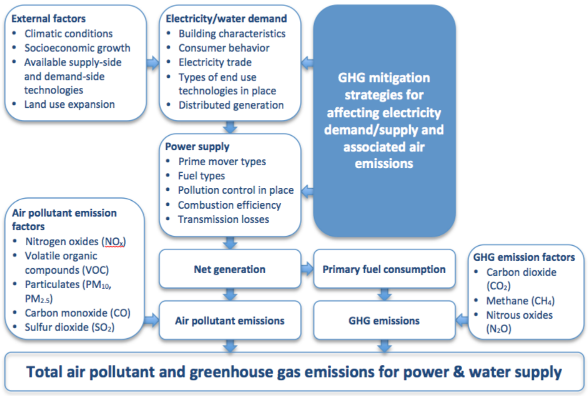


3.2 Power supply model

The power supply model aims to represent the capacity planning and dispatching of electricity within the Abu Dhabi Emirate. It includes all capacity, generation, and electricity transmission components that together comprise ADWEA operations. Power generation takes place in high-efficiency cogeneration stations where desalinated is co-produced. Power plant performance characteristics such as combustion efficiency, installed air pollution control equipment, and fuel type used of both existing and new generating technologies are used in combination with projected electricity demand to estimate annual emissions of air pollutants and GHGs. An idealized representation of the power supply model system is shown in Figure 4-2.

The model is able to capture changes in power supply system characteristics under Baseline (i.e., business-as-usual) conditions as well as under conditions of individual or collective implementation of GHG mitigation strategies. Baseline projections of total fuel consumption and gross electricity generation are based on ADWEC's most recent demand forecast until 2030 (Miller, 2013). Three key assumptions are being made in representing this forecast in the power supply model, as outlined in the bullets below.

Figure 3-2: Idealized representation of the power supply model



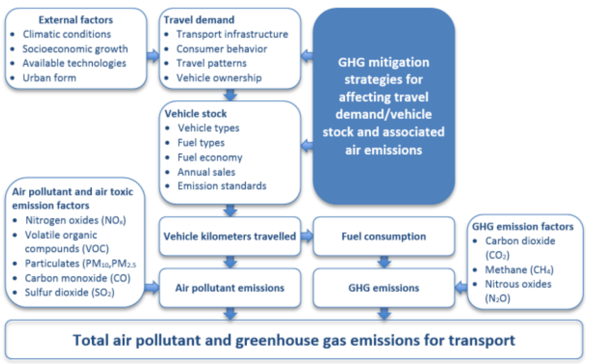
- *Location of future capacity.* First, as the location of unplanned capacity is unknown, a simplifying assumption was made that future electric generating units would be installed at or near the sites of current power stations, thereby defining the location of the stationary point source for the emission analysis.
- *Production-based.* Second, all power generated with the borders of the Abu Dhabi emirate is being considered even though a significant portion of electricity may be exported to other emirates. This assumptions aims to account for the fact that Abu Dhabi residents bear the environmental and public health impacts even though consumers outside the Abu Dhabi metropolitan area benefit from the production of electricity.
- *Out years.* Finally, the gross generation forecast for the years 2031-2035, for which there are no official estimates, is assumed to increase consistent with the forecast's overall average annual growth rate over the 2010-2030 period. CoMPAD contains detailed databases that hold the power station inventory in 2013 as well as projected fuel use and gross generation characteristics through 2035.

Annual air pollutant and GHG emissions associated with the power generation forecast depend on pollution control, emission factor, and combustion efficiency assumptions. Natural gas, the dominant combustion fuel used in the power plant fleet, consists of a high percentage of methane and varying amount of ethane, propane, butane and inert substances (USEPA, 1995). Combustion control (i.e., dry low-NO_x combustors) and flue gas recirculation (i.e., supplementary gas recirculation fans) are the primary methods used for reducing NO_x emissions in the Abu Dhabi power plant fleet. No other types of pollution control equipment have been installed, based on the data received thus far. Waste recovery using heat re-claimers is the only method being currently used to reduce GHG emissions, post-combustion.

3.3 Transport model

The transport model aims to represent current and future travel conditions within the Abu Dhabi Metropolitan Area. It codifies and integrates assumptions embedded in the travel demand model developed by the Department of Transportation for Abu Dhabi's Surface Transportation Master Plan (STMP; DoT, 2009, 2013 update). These assumptions apply to certain transport modes (i.e., on-road vehicles, metro), travel demand characteristics (e.g., trip patterns, growth in vehicle kilometers travelled), infrastructure conditions (e.g., public transport, roads, land use) and other parameters. Transport sector emissions associated with private, commercial and public on-road vehicles (i.e., cars, light trucks, heavy trucks, buses) or their displacement by electric-powered transport alternatives (i.e., metro) are accounted for in the model. All other modes - air, marine, recreational boating, military vehicles - are not addressed by the model. An idealized representation of the transport modeling system is shown in Figure 4-3.

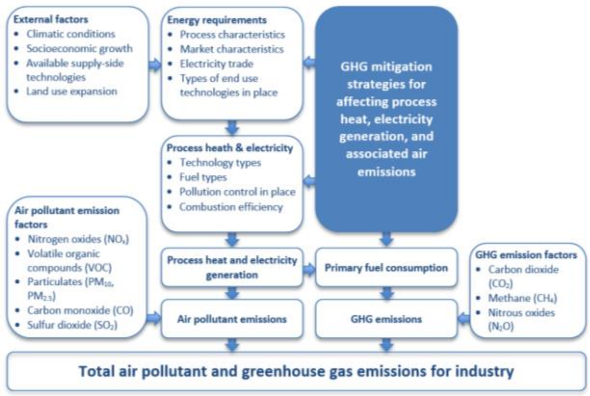
Figure 3-3: Idealized representation of the transport model



The model is able to capture changes in vehicle stock under Business-as-usual (i.e., the STMP) conditions as well as under conditions of individual or collective implementation of GHG mitigation strategies. The transport model accounts for fuel use and emissions for six on-road vehicle types. For light duty vehicles, these categories include motorcycles, sedans, and light duty trucks; remaining vehicle categories include heavy-duty trucks, buses, and mini-buses. Three fuel types are considered, namely gasoline, diesel, and compressed natural gas. Several assumptions are being made in representing the STMP in the transport model. First, car ownership levels for the years 2031-2035 is assumed to be consistent with the highest saturation achieved by 2030. Second, for categories that the STMP does not directly address (e.g., the number of heavy trucks), Base year stock levels were inferred based on relevant information contained in the STMP; End year stock levels were inferred based on average growth rates of suitable indicators. Third, the vehicle fleet in Abu Dhabi is consistent with modern and mostly recent-vintage (i.e., less than 10 years old) vehicle fleets found in European and Japanese markets. CoMPAD contains detailed databases that hold major vehicle stock characteristics and assumptions used in the transport model.

Annual air pollutant and GHG emissions associated with the above vehicle stock depend on a complex set of vehicle and fuel characteristics. For air pollutants, vehicles produce emissions throughout their service life, including during start-up, operation, refueling, and disposal (see Box 4-1), while additional emissions are associated with the refining and distribution of vehicle fuel.[6] International emission factors are well documented for a range of vehicle types and ages and can be applied to the vehicle fleet in Abu Dhabi. For GHGs, carbon dioxide is not controlled by pollution control equipment and is directly related to fuel consumption, while the other major GHGs (i.e., methane and nitrous oxide) are affected by emission control technologies. GHG emission factors are also well document and can be applied to the vehicle fleet in Abu Dhabi. For air toxics, only rough emission factor estimates are available as these pollutants have typically been unregulated. Rough estimates are being used based on available studies for application to the Abu Dhabi vehicle fleet. CoMPAD contains detailed databases that hold a summary of the emission factors used in the transport model for each of the vehicle types used in Abu Dhabi.

Figure 3-4: Idealized representation of the industrial model



> **Box 3-1: Factors affecting air pollutant emissions from vehicles (Cai, et al., 2013)**
>
> Vehicular air pollutant emission factors vary over time with advances in engine technologies, changes in fuel specification regulations, deterioration due to vehicle kilometer accumulation, implementation of tighter on-road emission controls such as inspection and maintenance (I/M) programs, and adoption of advanced emission control technologies, such as second-generation onboard diagnostics (OBD II), selective catalytic reduction, diesel particulate filters, and diesel oxidation catalysts.

3.4 Industrial model

The industrial model aims to represent current and future productive activities within key sub-sectors in the Abu Dhabi Metropolitan Area. Both onshore and offshore industrial facilities were considered. As a simplifying assumption, the focus of the industrial model is focused on four distinct activities at these facilities. For onshore facilities, the focus was on process heat and power generation aluminum production, and oil refining. For offshore facilities, the focus was on oil and gas operations. Together, these activities represent a large share of air emissions associated with industrial activities. An idealized representation of the industrial modeling system is shown in Figure 4-4.

[6] Air pollution is also emitted during the vehicular manufacturing process but that occurs in vehicle exporting countries (e.g., Japan, Korea, Europe, USA) whose emissions are assumed not to reach the Abu Dhabi Metropolitan Area.

The industrial model is the crudest of the three emission models in terms of its internal algorithms. This is primarily due to the nature of the data received which was relatively high-order (e.g., total annual emissions per facility) and generally sparse regarding activity (e.g., tonnes of steam per facility) or growth data (private sector growth plans).

4. Air quality modeling

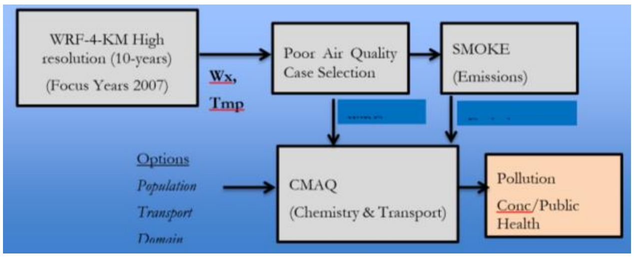
This section provides an overview of the air quality modeling approach used to estimate air pollutant concentrations associated with the implementation of Abu Dhabi's Climate Change Strategy. The section begins with a brief overview of essential framing issues. This is followed by a discussion of each of the air quality modeling components used in the study.

4.1 Introductory remarks and caveats

Air quality modeling for the Abu Dhabi Metropolitan Area was carried out using a parameterized process. This section summarizes our success, our struggles, and eventually our approach to air quality modeling portion of the study. From the beginning, we knew that it would be challenging to develop a robust and credible air quality model for Abu Dhabi that would provide adequate information to explore GHG strategies and their Co-Benefits to human health in relatively short study period. As discussed in the previous section, a fundamental starting point was the quantification of air pollutant emissions in the Abu Dhabi Metropolitan Area. Poor air quality is apparent in Abu Dhabi in the form of haze and degraded visibility, with the major contributors of this pollution from both anthropogenic (i.e., local pollutant emissions and transboundary pollutant transport) and natural sources (i.e., dust). As the focus of the Environmental Burden of Health Assessment was on the anthropogenic portion of air quality degradation (with natural cause being netted out), the calculation of public health co-benefits of emission reductions focused exclusively on the anthropogenic component.

The study team had conducted air quality modeling forecast research in the region, primarily around the propagation of dust (http://saudi-c3.rap.ucar.edu/cgi-bin/model/ugui.chem?range=GWPME) **using the same meteorological model used in this study (WRF)**. However, our group had little experience with the models that were both needed and thus chosen for this study- the air quality model (the Community Multiscale Air Quality Modeling System-CMAQ and the Sparse Matrix Operator Kernel Emissions model- (SMOKE). We believed that prior experience with other geoscience models would be adequate. In fact, the models chosen proved to be more difficult to implement over the Abu Dhabi Metropolitan Area than we had planned for and while progress has been made in their implementation, to date, we have had to simplify the air quality modeling that serves the heath modeling component of the study.

Figure 4-1: Initial conceptualized project elements, including: The Regional atmospheric modeling with the Weather Research Forecast (WRF) model; the selection of poor air quality days; the emissions inventory analysis using the SMOKE model; and the air quality modeling using CMAQ. These data feed the Public Health assessment model



The original conceptual approach is depicted Figure 5-1, and includes a cascade of models and their output to simulate air

quality over Abu Dhabi, and ultimately the impact on human health. The figure shows how the output from the regional atmospheric model serves as the boundary to the emissions and air quality model. Air quality modeling requires a representation of meteorology, pollutant emissions, including those from industrial and other human activities and emissions from natural sources such as desert dust and the sea-salt from oceans. These last two natural sources have a major influence on the local air quality throughout the Abu Dhabi Metropolitan Area. Meteorological processes, pollutant emissions, and air chemistry can be combined together to produce simulations of air pollutant concentrations that can be used to quantify their impacts on human health.

This cascade of atmospheric (i.e., from WRF) and air quality model information (i.e., from running SMOKE and CMAQ) was meant ultimately to provide input to the calculation of public health co-benefits within CoMPAD using the health model developed in the Environmental Burden of Disease Assessment. In the end, the inputs to health model are straightforward, and include the near- surface concentration annual average estimates of PM2.5, PM10, and ozone for each of the 4-km grid cells in the Abu Dhabi Metropolitan Area. However, establishing the baseline and future distributed emissions databases, and running SMOKE and CMAQ proved to be an intractable challenge despite consultations with other modelers and numerous attempts at numerical work-arounds. Therefore, a parameterized approach was develop to derive pollutant concentration estimates for the years 2007, 2035 (Bassline emission scenario) and 2035 (All-Policy emission scenario). This approach is discussed in detail in the sub-sections that follow.

4.2 Estimating Emissions using SMOKE

Ideally, the aerosol emissions from both anthropogenic and natural sources can be estimated using a modeling system such as the Spare Matrix Operator Kernel Emissions (SMOKE) Processing System. Since some emissions depend on meteorological parameters (such as temperature), the output of the meteorological model is also one of the inputs for SMOKE. Ideally, SMOKE produces emissions files that are then used as input to the air quality modeling. SMOKE manages emissions information from a complete set of point (industries), area (including homes and small businesses), mobile (vehicles), and natural sources, and distributes those emissions in space and in time. Problematically for this study, most of the SMOKE applications have been developed for the U.S., and so rich and complex datasets exist for that region, but not for the UAE. This proved to be a challenging problem, since modifying the database structure of SMOKE inputs to be compatible for the UAE proved to be insurmountable issue for this rapid assessment study. In theory, the quality of the SMOKE emissions estimates are directly compared with the other emissions datasets, local observations, and satellite observations. However, there are normally few direct measurements of emissions to compare against model estimates. Rather, the emissions estimates are tested indirectly when air quality model predictions are evaluated against measured atmospheric concentrations.

The purpose of SMOKE is to convert the resolution of the emission inventory data to the resolution needed by an air quality model (AQM). For this project, the AQM used was Community Multiscale Air Quality (CMAQ) modeling system. Emission inventories are available with an annual-total emissions value (e.g., tonnes/year) for each emissions source. CMAQ requires emissions stratified to an hourly basis, for each model grid cell, and for each model pollutant species. SMOKE ingests the emission inventory database to transform the estimated annual pollutants into the required input format required by CMAQ through temporal allocation, chemical speciation, and spatial allocation. SMOKE can process criteria gaseous pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOC), ammonia (NH3), sulfur dioxide (SO2); particulate matter (PM) pollutants such as PM 2.5 µm or less (PM25) and PM less than 10 µm (PM10); as well as a large array of toxic pollutants, such as mercury, cadmium, benzene, and formaldehyde.

SMOKE is a complex array of programs and processing scripts that takes the yearly emission inventories and processes the data to hourly estimates for a given day of the year for each grid cell in the CMAQ domain. The CMAQ domain is designed to incorporate meteorological forecast fields that are usually provided by the Weather Research and Forecast (WRF) modeling system. SMOKE also requires WRF output as input to process the distribution of pollutants for the diurnal cycle. SMOKE also attempts to distribute the emissions based on day of the week, holidays throughout the year, and other seasonal dependent attributes.

The emissions are stratified by the type of sources. The types include area, biogenic, mobile, and point sources. Area sources are usually defined as an area of pollutants such as an urban area that has many stores, gas stations, etc. The biogenic sources attempt to account for natural pollutants such as outside dust sources. Mobile sources include all vehicle types. There are two types of mobile sources that include vehicles driven off-road (e.g. heavy industrial construction (e.g., diesel dump trucks, loaders, etc.) and on-road (cars, motorcycles, buses, etc.). The final source type is point source which includes industry and power/water generation sources.

SMOKE was designed and primarily used for applications in North America. The system is designed to map all emissions to state, county (or provinces in Canada), and tribal codes defined in the US, Canada, or Mexico. All the configuration files for the setup and operation has been engineered to be used in this modeling space. The challenge is to adapt the system designed for North America to the Abu Dhabi context. For this project, research was conducted on how to adapt SMOKE for Abu Dhabi for this rapid assessment. This undertaking proved problematic. This was because, in addition to the detailed emission inventories that were developed using the emission models described in the previous section, additional detailed emission inventories were needed for the Arabian Peninsula region. In addition, there were a large number of technology-specific requirements for the Abu Dhabi emissions database that required making a series of near-heroic assumptions. Hence, after extensive evaluation, it was determined that given the time constraints and level of effort, that it would not be possible to develop this regional emission inventory, and in fact, such an inventory would likely be a research sub-project unto itself.

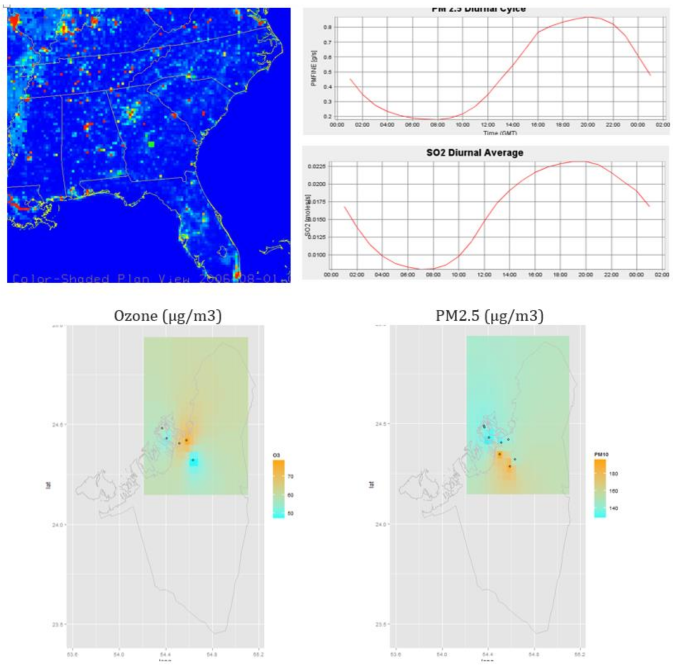
The project team benefited from SMOKE training, which provided a basis for processing and merging area, mobile, and point emissions for a case study in the US. Although the course proved useful for understanding the basic SMOKE processing steps, the SMOKE developers confirmed that applying SMOKE outside the US was a very difficult and complex task, requiring months-if-not-years years of air quality modeling and expertise, suggesting its applications outside the US would require a significant level of effort (1+ year) to be done correctly. Ideally, a unique SMOKE application would be developed for the Arabian Peninsula region, including the UAE (e.g., creation of a UAE-SMOKE version).

Regardless, the project team attempted to convert and adapt SMOKE for this study focusing on the Abu Dhabi Metropolitan Area. The first step was to create "country", "state" and "county" definitions (defined in the SMOKE COSTCY file). The original COSTCY file only contains a database for the US, Canada, Mexico and a few US territories. GIS tools were used to define these boundaries. The precincts of Abu Dhabi were used to create the county boundary definitions. Once defined, all sources needed to be defined by country/state/county codes that are unique for each type of emission. Also, each emission is required to be identified by a Source Classification Code (SCC), which is an 8 digit identifier. This SCC provides a summary of emission type. For example, "External Combustion Boilers; Electric Generation; Lignite; Spreader Stoker" is represented by 10100306. There is over 10,000 types of codes, again, designed for sources found in North America. A significant amount of research was done by searching various publications and previous studies in an effort to determine which SCC's were most representative to Abu Dhabi. Additionally, 5-digit U.S. Federal Implementation Planning Standards (FIPS) state and county codes had to be "created". These are readily available in a variety of databases for the US, but do not exist for countries like the UAE.

Another major processing step was the creation of a database for mobile sources. The emission database contained inventories for cars, light duty trucks, taxis, motorcycles, heavy duty trucks, transit buses, and mini-buses. In the SMOKE processing systems, there are thousands of options for the types of vehicles (e.g., gas, diesel, type of engine, type of breaking, how much idling, etc.). Also, SMOKE requires information about the rate per distance of each type of vehicle, vehicle miles traveled, and speed of the vehicle. Although this specific type of information that needed to be provided to SMOKE was readily available from the transport emission model, there were many other types of information that were unavailable and difficult to make defensible assumptions. A significant effort was made to research how to generate this information in a systematic and robust manner. The process that was conducted was to use the population of each precinct to stratify the vehicles. In each precinct, vehicle speed and average miles traveled were estimated. However, this proved to be very uncertain, since this information was not readily known.

Emissions from stationary sources like power stations and industrial facilities also had to be processed. In SMOKE, each new point source is provided as a unique code to identify the source (e.g., any source for an electric power plant to a gas station gets a unique ID). This information had to be created for Abu Dhabi. It was not clear on how to do this step and research has been in progress on how to approach this issue. In the US, a surrogate database is also available for the EPA and other sources. This database is used to distribute to stratify the fractional amounts of pollutants from different sources into the different county regions. The challenge was if and how to create this surrogate database for the UAE. Additionally, the grid domain required processing and adaptation to ingest all the input data including the WRF fields and provide a grid that can be used directly with CMAQ. After many trials, it was still unclear how adapt the different grids into the processing system.

Figure 4-2: Development of SMOKE 'surrogate' file based on an average of the SE US and local sources



After about three months of continuous effort, it was determined that the use of SMOKE was not feasible. Therefore, a more simple air quality model was employed to distribute the emissions around Abu Dhabi. This air quality model used a simple plume dispersion for point source and propagation of mobile sources using WRF derived wind fields. It also used coarse grid CMAQ emission from a previous study conducted by UNC for the background emissions. This setup provided reasonable results for the annual emission distributions. However, it would be recommended to continue this study in the future with the more complex SMOKE/CMAQ AQM system to improve the sensitivity to the diurnal, seasonal, and meteorological variations observed in Abu Dhabi. This advanced modeling along with systematic verification would provide estimates of the uncertainty of the first order AQM approach.

4.3 SMOKE Work-Around

Since we were not able to generate a valid emission database and thus a SMOKE output file for the UAE to serve as input to the CMAQ air quality model, we developed a simplified approach that made use of a valid SMOKE model for the southeastern U.S. This emissions file includes a 24-hour diurnal cycle of the average emissions for the region depicted in the map of the southeastern US, with a single hour estimate shown for PM2.5 (see Figure 5-2). The spatial average of emissions at each hour were estimated over this domain and are shown for two representative emissions, -PM2.5 and SO2 on the right of the figure. Then, local mobile and stationary sources were added to the average background values. The spatial distribution of the observed PM2.5 spatial and O3 emissions are shown below (O3 is a CMAQ model output).

4.4 CMAQ Air Quality Modeling

Dust plays an important role in air quality modeling. Throughout the literature there is a consensus that the frequent and severe dust storms that are characteristic of the region play an important role in PM exposures. The highest observed PM10 concentrations exceed the standard several-fold, and are clearly associated with periodic dust storm events. One study, using data from 1994 to 2003, has reported that Abu Dhabi experiences on average of 3-8 dust storms annually, 10-20 dust events, and a total of 242 days with haze conditions (Villers et al., 2007).

An important weather phenomena associated with dust storms are immense walls of blowing sand and dust called Haboobs. Emiratis and others in the Middle East refer to haboobs as intense local storms that produce large quantities of dust, while shyamal winds cause more regional-scale dust episodes. Haboobs were the focus of investigation during UAE2 and Miller et al., 2008 used satellite, radar, lidar, and meteorological station data to study their formation and dynamics. Those authors developed an idealized model of haboob dust production and predicted that 30% of the regional-scale total dust production in a 1000x1000 km domain around the United Arab Emirates and could be attributed to haboobs. These studies are useful in our understanding and simulation of these important meteorological phenomena. It is critical for accurate aerosol predictions that the atmospheric and air quality models be able to properly simulate the land sea circulations in the UAE and dust events such as Haboobs and Shamal.

As noted earlier, the Community Multiscale Air Quality (CMAQ) model was the original model chosen for air quality modeling. CMAQ is one of the leading air quality models internationally, and takes inputs from WRF and SMOKE and models the transport, chemical transformations, and removal of pollutants in the atmosphere. The pollutants include primary pollutants that are emitted directly, such as carbon monoxide and dust, and secondary pollutants that are formed in the atmosphere, such as ozone and sulfate aerosols. CMAQ is a 3-dimensional gridded model, whereby the atmosphere is divided into a 3-dimensional matrix. Within each cube of the matrix and at each time step, the concentrations of many air quality pollutants are simulated, as a result of emissions, transport, chemical reactions, and deposition. CMAQ simulations produce estimates of the concentrations of many pollutants in three dimensions over the entire model domain and vary by hour over the simulated time horizon. While this sounds straightforward, one must remember the strong connection between regional atmospheric process and local emissions. While the CMAQ simulation can produce many air quality consistent values, in the context of this GHG Co-benefits study, the necessary output from the model would only be annual average PM10, PM2.5, and O3 concentrations.

Ideally, air quality simulations from CMAQ would be compared against measurements of pollutant concentrations from surface air quality and satellite observations. The single largest uncertainty in air quality models is typically the emissions inputs, but there are also uncertainties in the meteorological models and in the representations of chemical and physical processes within the air quality model itself. The pollutants include primary pollutants that are emitted directly, such as carbon monoxide and dust, and secondary pollutants that are formed in the atmosphere, such as ozone and sulfate aerosols.

The original approach was for the CMAQ air quality modeling outputs to serve as inputs to the health model. Estimates of ambient pollutant concentrations at ground level in CMAQ are combined with information about the location of the population, health characteristics, and PM10, PM2.5, and ozone concentrations. There is a need for the proper quantification of the temporal transport of anthropogenic emissions from Europe, and sources of dust from the Arabian Peninsula. In addition to transport issues, the region has complex land sea interaction that result in an intricate vertical stratification of pollutants. The lack of routine observational data for the region, which is needed to properly evaluate model performance is especially relevant for PM measurements and our understanding of the composition and source apportionment of that pollutant. The relatively little data that exists on this suggest significant fractions of PM2.5 are from fossil fuel combustion, and that a large fraction of PM10 consists of coarse dust. Finally the availability and quality of data on regional emissions is a critical limitation for regional air quality modeling, particularly the availability of industrial emissions, transportation emissions (especially with the rapid growth of the local and regional population), and particularly for emissions outside the Abu Dhabi Metropolitan Area.

In our attempt to run the CMAQ model, we took our idealized SMOKE emissions data, and setup CMAQ to simulate the regional air quality based on the WRF forcing dataset and time periods evaluated through a Self-Organizing Map analysis. We encountered problems in the configuration of the CMAQ model, primarily due compilation challenges and challenges due to the meteorological input fields from WRF. After considerable effort to compile the SMOKE and CMAQ software on a local NCAR Linux cluster, we discovered that the original 4-km domain was simply too large for CMAQ and its deployment on that cluster (known as hydro-C1). As a first step, we had to reduce the domain from its original dimensions of NCOLS=368 to NROWS= 346 to NCOLS = 174 and NROWS = 164 for the model to execute.

Next, we discovered domain configuration issues. When WRF was originally run for the LNRCCP's regional atmospheric modeling study, the model was configured onto a Mercator projected coordinate systems. CMAQ, on the other hand, is typically run using a forcing dataset on a Lambert Conformal Projected domain. After considerable exchange between the authors of the CMAQ geographic projection system known as the IO-API[7], it was concluded that the CMAQ system needed the WRF output on the Lambert Conformal projected coordinate system. Unfortunately, re-running WRF was not possible because it would have taken too long to re-run the experiments and thus was outside the scope of the co-benefits sub-project. In the end, it was clear that an alternative approach was needed in order to provide the necessary results for evaluating the GHG reduction co-benefits on human health. This is described in detail in the next sub-section.

[7] Personal communication with Dr. Carlie Coats.

4.5 Refined Methodology

This section provides a detailed description of the refined methodology used to estimate air pollutant concentrations associated with the results of local emissions modeling. This refined methodology is the basis for estimating the air quality for a baseline year defined as period centered on the year 2007 and estimates for a future climate scenario defined for the period around 2035. In 2035, local emissions from two projections that assumed different levels of GHG mitigation policies were evaluated. The first scenario, defined as the "Baseline" Scenario assumes that there is no reduction in emissions in the Abu Dhabi region. The second scenario defined as an "All-Policy" Scenario integrates all 17 initiatives in Abu Dhabi's Climate Change Strategy to reduce emissions in the Abu Dhabi Emirate.

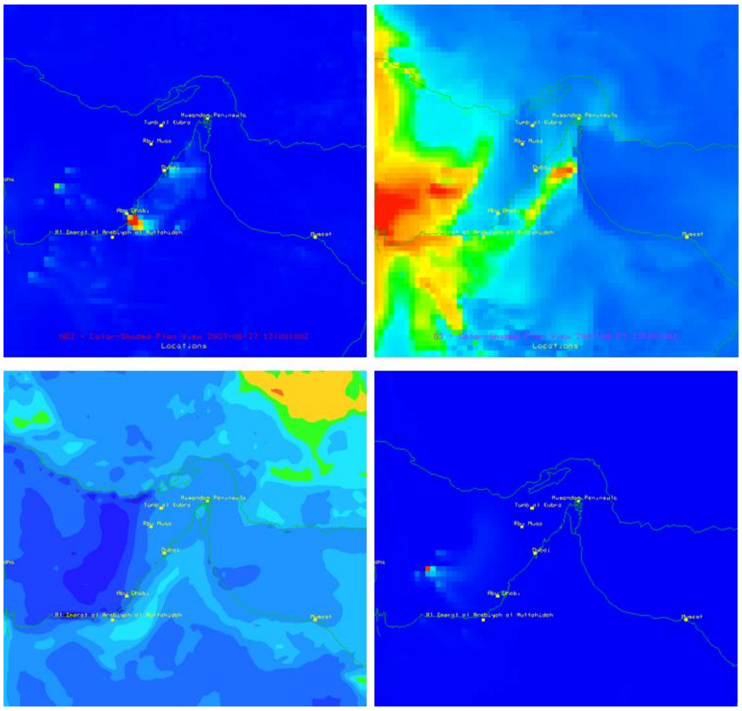
Given the inability to adequately run both the SMOKE and CMAQ regional air quality modeling components, this study evaluated the air quality in Abu Dhabi using a combination of background emissions estimated from a CMAQ modeling effort undertaken by researchers at the University of North Carolina as part of the Environmental Burden of Disease Assessment (hereafter "UNC study") and meteorological data derived from the WRF experiments. UNC used WRF simulations of atmospheric fields for current and future climate, surface observations from air quality monitoring stations located in the Abu Dhabi Metropolitan area, surface observations from the Abu Dhabi airport weather station (OMAA), and atmospheric soundings observed the Abu Dhabi Airport (OMAA). Current and future emissions were estimated for mobile sources which includes the distribution of vehicles and for onshore/offshore power/water production and industrial facilities. The following discussion provides a detailed description of the methodology and assumptions made to compute emission estimates for an 84 km x 84 km domain at a grid resolution of 4 km centered on Abu Dhabi.

The refined methodology aimed to estimate the annual average concentrations for the following emissions: carbon monoxide (CO), sulfur oxides (SOX), nitrogen oxides (NOX), volatile organic compounds (VOC), particulate matter for sizes 2.5 µm or less (PM25), particulate matter 10 µm or less (PM10) and ozone (O3). The first step was to estimate the background emissions that would be present in the domain from sources observed regionally (e.g., Middle East) or globally (e.g., Europe, US, etc.). Background emissions could be estimated from global databases such as Emissions of atmospheric Compounds & Compilation of Ancillary Data (ECCAD) or from regional emission studies that have already incorporated global estimates at a higher resolution (e.g., the UNC study).

Table 4-1: UNC 12 km CMAQ baseline emission dataset.

Period	Start Date	End Date
1	01-May-2007	30-July-2007
2	15-December-2007	28-March-2008

Figure 4-3: Example UNC CMAQ 12 km output for NO2 (top left), O3 (top right), PM2.5 (bottom left), and SO2 used to compute the background emissions fields



In this study, the UNC CMAQ database was used for background (i.e., non-local) emissions. The UNC study evaluated emissions over the UAE at a grid resolution of 12 km and temporal resolution of one hour. Emissions were estimated for two temporal periods. The two study periods evaluated the UNC study were 1 May 2007 – 30 July 2007 and 15 December 2007 – 28 March 2008 (see Table 5-1). This provided a total of 277 days to estimate the annual background emissions. The UNC dataset generated 145 emission fields, but only a small subset were used in this study. Figure 5-3 shows examples of the NOX, O3, PM25, and SOX emission fields using in the analysis. The dataset does not provide a full year to generate the yearly average estimates, which has the potential to introduce uncertainty in this study. However, the UNC study focused on spring and summer and a winter to spring periods. These two periods likely captured most of the annual variability and was assumed to provide a representative dataset for the background emissions.

The UNC CMAQ emissions dataset was further processed to create a subset data centered over Abu Dhabi. A 240 x 240 km (20 x 20 grid) subset was extracted over the Abu Dhabi domain. This grid was used to compute an area averaged emission estimates for each pollutant. The area averaged estimates were used to compute the annual background estimate of each pollutant.

The UNC CMAQ emissions data were extracted and processed used a set Climate Data Operator (CDO) scripts.[8] The first step in using the CDO tools was to extract required pollutants to estimate the background emissions. In the CMAQ dataset, the fields extracted were: CO (carbon monoxide), NO2 (nitrogen dioxide), SO2 (sulfur oxide dioxide), O3 (ozone), A25J (PM25), and A25J + ACORS (PM10). In the CMAQ dataset, the pollutants NO and NO3 were also available. However, they represent less than 1% of the total NOX and were not included to improve computational efficiency. SO2 was the only sulfur oxide field included in the UNC CMAQ dataset. Note that VOC is not included the UNC CMAQ dataset. A global VOC

[8] For more information, see https://code.zmaw.de/projects/cdo

estimate was used for background emissions. From various studies, the background VOC emissions was set to 2 μg/m^3 (http://www.air-quality.org.uk/04.php).

Table 4-2: Summary of background emission values computed from the UNC CMAQ dataset

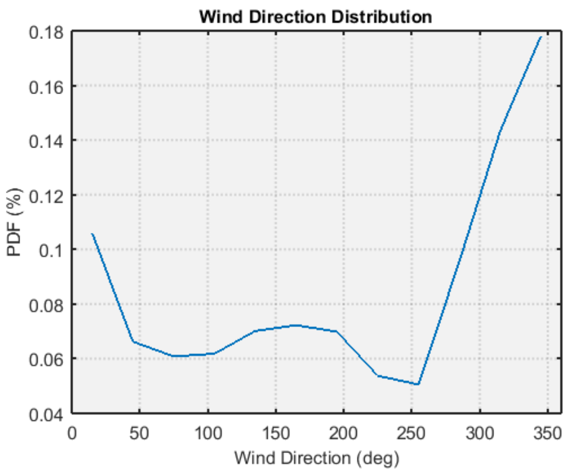
Pollutant	Value (μg/m^3)
CO	127.8
NOX	4.3
SOX	4.5
O3	105.5
PM25	14.8
PM10	16.0
VOC	2.0

The second step in the CDO processing sequence was to extract a 20 x 20 grid domain centered on Abu Dhabi for each pollutant. These data were used compute the daily average and then the area average for each pollutant. The final step was to estimate annual average using the 277 daily area averaged pollutant estimates. The UNC CMAQ emissions are stored in parts per million (ppm). These units needed to be converted to parts per billion (ppb) and then converted to μg/m^3 for direct input into the health impact model. The equation used to convert the concentration in ppm to μg/m^3 is as follows:

*Pollutant Concentration (μg/m^3) = Pollutant Concentration (ppm) * 1000 (ppb)/1 (ppm) * (molar mass (g/mole))/molar volume (L))*

A summary of each background pollutant is found in Table 5-2. These estimates were then applied to each study domain grid cell. It was assumed that the background emissions did not change between the baseline and current climate scenarios and were used for all three estimated field (2007-Baseline, 2035-BAU, 2035-BAU). Estimating the change in global emissions was outside the scope of this study, but will likely be small over the relatively short time period between 2007 and 2035.

Figure 4-4: The probability distribution of wind computed from 2007 WRF simulation and OMAA airport observations.

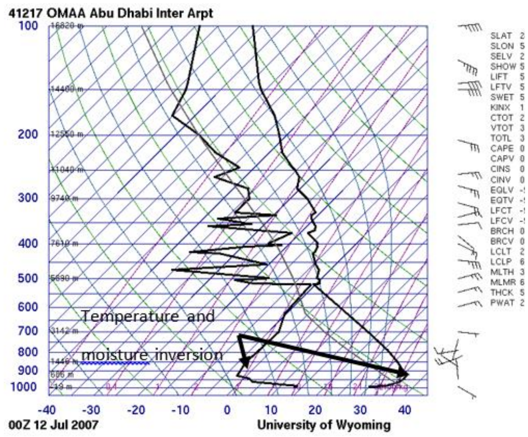


The next step in the data analysis was to process and integrate the point source emission inventories from power supply and industry into the study domain. There were a total of 21 point emission sources in and around the Abu Dhabi. The emission inventories were estimated in total tonnes per year. The emissions needed to be distributed downstream of the source. The amount of emissions distributed downstream were estimated by combining the distribution wind direction over Abu Dhabi along with a simple plume dispersion model. To estimate the distribution of wind direction over a seasonal cycle, WRF output at a 4 km resolution was processed for the year 2007. The distribution of wind on an hourly basis was extracted from the grid cells over Abu Dhabi and then averaged to obtain an area averaged wind direction estimate. These results were compared with the surface observations at the Abu Dhabi Airport (OMAA).

The probability distribution function (PDF) of this wind direction analysis is shown in Figure 5-4. The results show that the wind direction is out of the north to northwest significant fraction of the time with a peak of about 18% with winds directly from the north. The minimum in wind direction is out of the southwest (250°) which only occurs about 3% of the time during the year. This PDF was then used as a weighting function to distribute the annual total of pollutants in each direction from a given point source. For example, at each point source, 18% of the total annual emissions were distributed to the south of the source. One assumption was made was the emissions were steady state and uniformly distributed in time a given year. The impact of this assumption would need to be explored in future studies.

As previously noted, air pollutant emission inventories were provided in tonnes/year. However, the health model requires air pollutant concentrations in units of micrograms per cubic meter (i.e., μg/m^3). The emissions were first distributed in the direction of the wind and spread uniformly over the plume area using the plume dispersion model. To obtain a concentration, the emissions must also be distributed vertically in the atmosphere. The atmosphere is generally well-mixed up to the boundary layer (e.g., the level of the first temperature and moisture inversion). Atmospheric soundings were processed to estimate the average boundary layer height. Based on this analysis, the average boundary layer height was estimated to be around 1 km (1000 m) over Abu Dhabi. A typical sounding from the Abu Dhabi Airport supporting this assumption is shown in Fig. 5-5. The average concentrations were then computed for the volume outlined by the plume area and the vertical height to the average 1 km boundary layer height. Once all the emissions were distributed downstream of the source, the emissions for each point source were then accumulated at each grid point to get the total emissions for each point source for each pollutant.

Figure 4-5: Typical atmospheric sounding with showing the persistent low-level temperature.

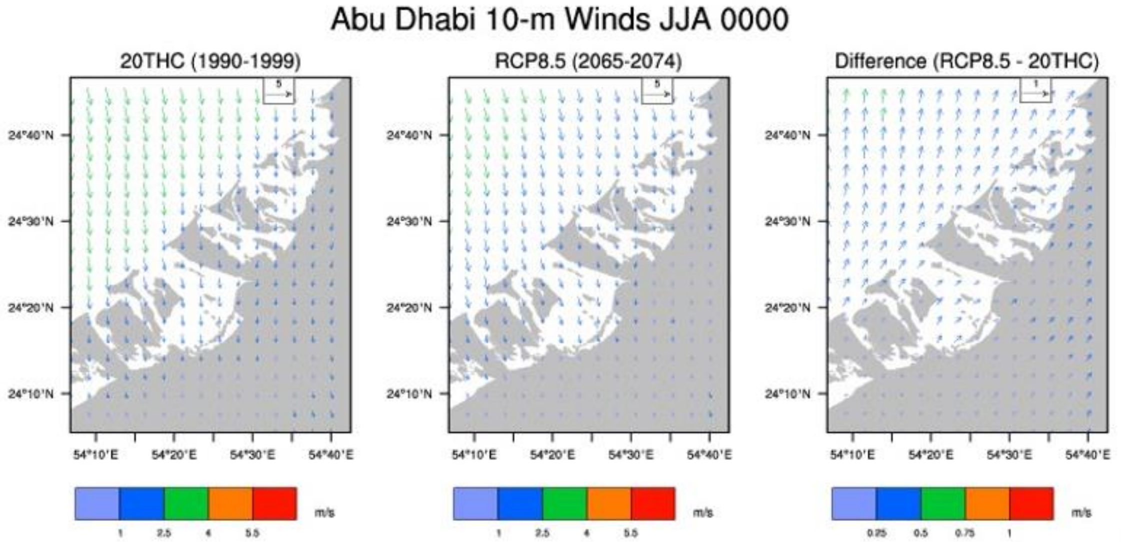


The point source processing was conducted for the 2007-baseline, 2035 BAU and 2035 Policy future climate scenarios. For the future climate scenarios, the projected future climate change for the wind field was incorporated into the analysis. The change field was computed using the future climate WRF output analysis that done in the regional atmospheric modeling sub-project (LNRCCP, 2015a).

An example of the wind change vector field is shown in Fig. 5-6. An average change vector was computed from the difference field. The average change vector was applied to the PDF of the wind direction field shown in Fig. 5-5. The emissions were then distributed downwind of each emission source using the adjusted wind direction PDF. The point source emission were then accumulated at each grid point using the same procedure used for the 2007-baseline year.

The next step in the emission and air quality processing procedure was to generate the distribution of emissions from mobile sources. Mobile emission sources were composed of

Figure 4-6: Typical atmospheric sounding with showing the persistent low-level temperature and moisture inversion.



seven categories of motorized vehicles that includes cars, light duty trucks, taxis, motorcycles, heavy duty trucks, transit buses, and mini-buses. The emissions were distributed based on the fraction of the total population living in each precinct. Using geographical information system (GIS) toolbox program called ARCMAP, the boundaries of each precinct was mapped onto the 4 km resolution study domain. The fractional amount of the total emissions for each pollutant was then distributed uniformly throughout the area of each precinct based on the population in the precinct. Once the emissions for each pollutant and vehicle type was distributed in the precincts, the total mobile emissions were accumulated to obtain the total mobile emissions at each grid point in the domain. These steps were repeated for the mobiles emissions estimated for 2007-Baseline and for the 2035-BAU and 2035-Policy scenarios.

The emissions from the background, point, and mobile sources were integrated together for pollutants CO, NOX, SOX, VOC, and PM25 for the 2007-baseline, 2035-BAU and 2035-Policy scenarios. One challenge in this analysis methodology is to estimate the distribution of ozone. The total concentration ozone generated near the surface is dependent on amount of emissions such NOX and to lesser degree VOC observed in the boundary layer. The UNC CMAQ output provided estimates of the background ozone emissions. For the 2007 base year, ozone emissions were estimated using the observations from available air quality monitoring stations located around Abu Dhabi. The distribution of ozone was then estimated by using the spatial distribution pattern of the NOX emissions and scaled to the distribution of ozone observed at the air quality monitoring stations for the 2007-Baseline year. For the climate change scenarios, the NOX change fields for 2035-BAU and 2035-Policy were used to adjust the level of ozone from the 2007-baseline. The spatial distribution of ozone was mapped to the spatial distribution of NOX for the climate change scenarios.

Concentrations of PM10 were derived from information about PM2.5 emissions. That is, the EBDA assumed that PM10 was related to PM25 concentrations by the follow relationship:

PM10 = PM25/0.35. This relationship was also used to create the PM10 emission fields point and mobile sources.

The final step was to merge all the emissions for the background, point, and mobile sources for each pollutant at each grid cell. This processing step created the final merged emissions gridded field for CO, SOX, NOX, VOC, PM25, PM10, and O3 for the 2007-Baseline and climate change scenarios for 2035-BAU and 2035-Policy. Figure 5-7 shows example of the merging of the background, point, mobile and total combined fields for NOX for the 2035-Policy emissions. The final combined NOX emissions for 2007-Baseline, 2035-BAU, and 2035-Policy are shown in Fig. 5-8.

A continuation of this study would include the implementation of high-resolution 4 km CMAQ simulation over the Abu Dhabi domain. Emission inventories would be reprocessed using an inventory preprocessor such as Sparse Matrix Operator Kernel Emissions (SMOKE) or CONsolidated Community Emissions Processing Tool (CONCEPT). SMOKE and CONCEPT are complex emissions processing codes that distribute annual emissions based on local information such as seasonal and diurnal cycle, local meteorology, vehicle inventories, driving rules and local holidays. These tools have been developed for the US. These tools require significant time and resources to develop similar databases and mapping information (e.g., county boundaries) for the UAE. However, implementing emission inventory tools such as SMOKE and CONCEPT could reduce uncertainty of the assumption of a steady-state point and mobile emissions that was used in this study would be recommended for future studies.

Figure 4-7: Individual emission contributions for background (upper left panel), point (upper right panel), mobile (lower left panel), and combined emissions for NOX. The example is for 2035-Policy scenario. Units are in μg/m³..

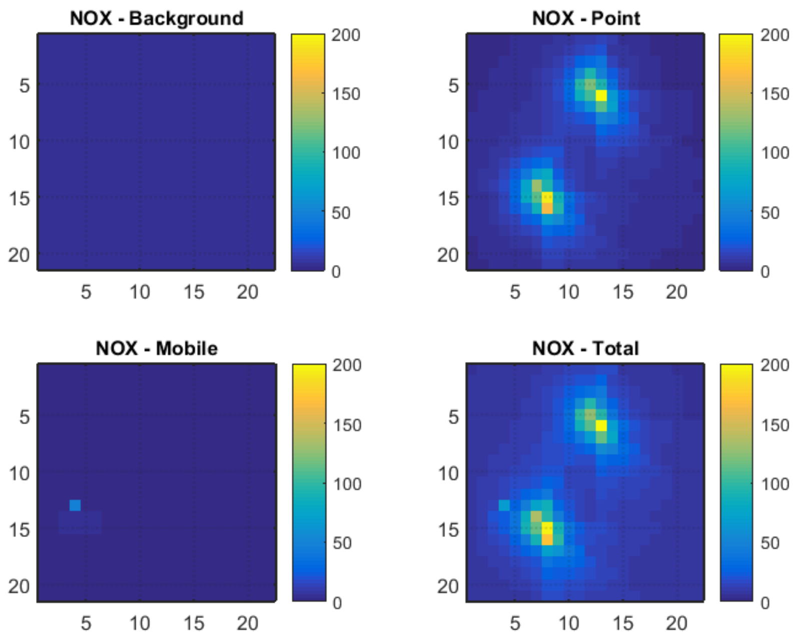
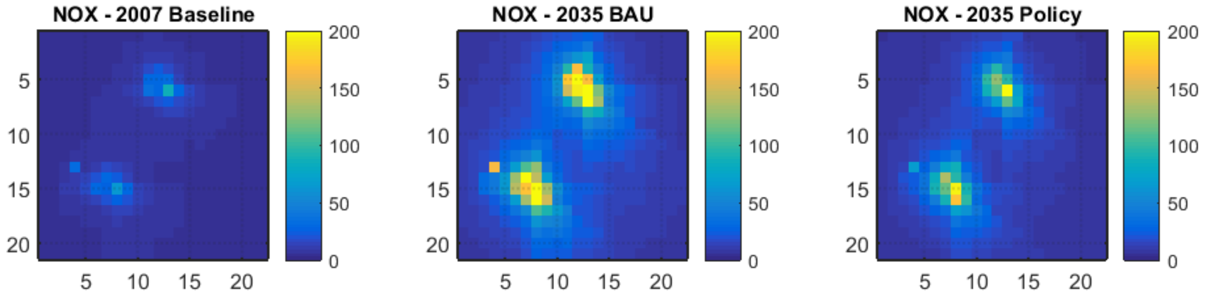


Figure 4-8: Final gridded emission products for NOX for 2007-Baseline, 2035-BAU, and 2035-Policy



To improve the annual spatial distribution of emissions, a combined implementation of high-resolution 4 km WRF and CMAQ integrated with emission inventories processed with SMOKE or CONCEPT for entire year simulation for both the baseline and climate change scenario BAU and Policy emission estimates could provide a more realistic spatial distribution of pollutants distributed around Abu Dhabi. The non-steady state atmospheric parameters such has diurnal and seasonal cycles of wind speed and direction, temperature, and humidity using WRF with CMAQ could provide more realistic propagation of the emission plumes from the point and mobile sources. However, a detailed verification study should also be conducted using modeled atmospheric conditions with WRF and air quality simulations with CMAQ to determine if they the fields are representative of observed conditions and provide uncertainty estimates for the results.

The future climate scenarios would also benefit from year-long simulations of future atmospheric conditions along with projected emissions from point and mobile sources. The WRF simulations of future climate would provide estimates of temperature, wind, and humidity changes to better represent that change field and propagation of pollutants downstream of the source. Finally, future background emissions could be improved by including future global estimates of emissions if they are available from independent studies. However, there is likely much uncertainty in the future global emission estimates and the steady-state assumption used in this study could be reasonable.

Public health co-benefit modeling

This section provides an overview of the modeling approach used to estimate the public health co-benefits associated with reductions in air pollutant concentrations due to the implementation of Abu Dhabi's Climate Change Strategy. The section begins with a brief overview of essential framing issues. This is followed by a discussion of each of the modeling components used to estimate the magnitude of public health co-benefits accrued from the GHG mitigation policies.

4.6 Introductory remarks

Public health co-benefit modeling relied exclusively on the algorithms in the health model developed as part of the EBDA for outdoor air pollution. This model was developed using

UAE-specific health and population data for the year 2008. Such data were used in combination with a set of concentration-response coefficients obtained from a duly referenced set of epidemiological study references. No other concentration-response coefficients than those cited in the EBDA were used to derive estimates of public health co-benefits. The EBDA assumed centrsal values and various algorithms were codified within CoMPAD and used to estimate public health co-benefits.

4.7 Structure of the health model

The structure of the EBDA health model consists of separate submodules devoted to PM10, PM2.5 and O3 within the "Outdoor Air Pollution Globals Module". Each of these submodules is comprised of the same structure consisting of individual nodes that represent entry points for the range of required data and assumptions. A description of the PM10 submodule is provided in Figure 6-1 as an example. Figure 6-1a describes the individual nodes that make up the submodule; Figure 6-1b provides a flow chart of the calculation sequence, or influence diagram. Each of the major nodes listed in this Figure are discussed in the subsections that follow.

4.8 Health endpoints

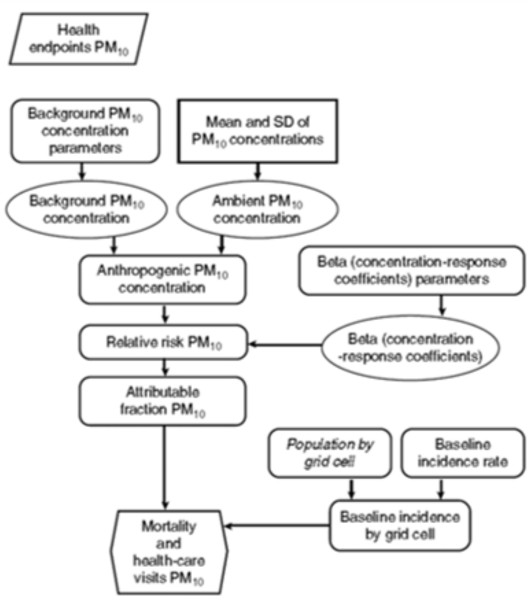
Health endpoints are defined as the outcome of the impact of pollution on human health. In the EBDA, two health endpoints are modeled, premature deaths and excess health-care visits. The former refers to mortality in adults over 30 years of age and children under 5 years of age that can be directly attributed to outdoor air pollutant after background pollution from natural and transboundary pollution have been netted out. The latter refers to morbidity effects that can be directly attributed to outdoor air pollutant after background pollution from natural and transboundary pollution sources have been netted out. The values assumed for each of these endpoints are summarized in Figure 6-1c.

Figure 4-9: PM10 sub-module in Abu Dhabi's EBDA (MacDonald Gibson, et al., 2013)

a) Description of nodes

Name of node	Description	Equation
Health endpoints PM_{10}	Number of deaths associated with short-term exposure to ambient PM_{10}: all-cause mortality and respiratory mortality in children under 5 (Table 4.7).	
Background PM_{10} *concentration parameters*	This study assumes a wide range of natural background that is uniformly distributed. In the measurement-based approach, the minimum and maximum values are assumed to be 10 and 90 μg/m³; in the CMAQ-based approach, the minimum and maximum values are assumed to be 10 and 50 μg/m³.	
Background PM_{10} *concentration*	This variable specifies the shape of the probability density function of the background PM_{10} concentration as uniform and calls the parameters entered in the parent node *Background* PM_{10} *concentration parameters*.	*Uniform (low, high)*
Mean and SD of PM_{10} *concentrations*	Means and standard deviations (SD) of PM_{10} concentrations in each grid cell, estimated by the UAE outdoor air quality modeling group (using the measurement-based or the model-based approach).	
Ambient PM_{10} *concentration*	Annual ambient PM_{10} concentrations in 2007–2008 in each grid cell, defined as lognormally distributed and characterized by mean and standard deviation.	*Lognormal (mean, SD)*
Anthropogenic PM_{10} *concentration*	Ambient PM_{10} concentration as a result of anthropogenic pollution, estimated by subtracting the background concentration from the ambient concentration.	*Ambient concentration – Natural background*
Beta (concentration-response coefficients) parameters	Concentration-response coefficient from literature, defined as normally distributed and characterized by mean and standard deviation.	
Beta (Concentration-response coefficients)	This variable specifies the shape of the probability density function of the concentration-response coefficients as normal and calls the parameters entered in the parent node *Beta (concentration-response coefficients) parameters*.	*Normal (mean, SD)*
Relative risk PM_{10}	In epidemiologic studies, relative risk (RR) is defined as the exponential function e to the product of anthropogenic concentration and concentration-response coefficient (β, see Eq. 4.3).	$RR = e^{\beta \Delta x}$
Attributable fraction PM_{10}	By WHO's definition (Ostro 2004), attributable fraction (AF), meaning the fraction of a certain health outcome that is attributable to exposure to the environmental health risk of interest (see Eq. 4.2).	$AF = \frac{RR-1}{RR}$
Population by grid cell	An alias of the node *Population by grid cell* in the *Outdoor Air Pollution Globals* Module.	
Baseline incidence rate	Calculated by dividing the total incidence (in this case, the total number of deaths) in an emirate by the total population in that emirate.	$\frac{\text{Health endpoints } PM_{10}}{\text{Population}}$
Baseline mortality	Baseline mortality among the population studied for 2008, equal to baseline mortality rate multiplied by the study population.	*Baseline incidence rate × Population*
Mortality PM_{10}	Annual number of deaths attributable to exposure to ambient PM_{10} in 2008, equal to baseline mortality multiplied by AF. Deaths in each grid cell are aggregated to obtain the total mortality due to PM_{10} by emirate as well as in the whole UAE.	*Attributable fraction × Baseline mortality*

b) Influence diagram



c) Assumed values

Cause-specific mortality and health care facility visits in Abu Dhabi, 2008

Value	Health Endpoint
2949	All-cause mortality
2075	All-cause mortality in adults over age 30
412	Cardiopulminary mortality in adults over age 30
68	Respiratory mortality in adults over age 30
38	Lung/trachea/bronchus cancer mortality in adults over age 30
9	Respiratory mortality in children under age 5
97271	Respiratory health-care facility visits
135021	Cardiopulminary health-care facility visits

Source: Table 4.7 of *Chapter 4* of the UAE Environmental Burden of Disease Assessment
Note: The ratios developed from these enpoint values are held constant over the planning period

4.9 Background pollution levels

Background pollution levels are defined as concentration of air pollutants in the atmosphere that is unrelated to anthropogenic activities within the UAE. For the purposes of the co-benefits analysis, only particulate matter and ozone were considered, as these were the pollutants modeled in the EBDA. The source of this pollution is either natural (i.e., particulate matter from dust storms) or anthropogenic (i.e., transboundary pollutant transport from other countries), or from unidentified sources. The values assumed for particulate matter (PM2.5 and PM10) and ozone are summarized in Table 6-1. These levels of background air pollution were assumed to remain constant over the 2007-2035 time period.

4.10 Beta coefficients

Beta (β) coefficients are the concentration-response relationships that were derived from international epidemiological research studies in the EBDA. They represent a relationship between the *concentration* of a pollutant in the atmosphere and the health *response* (e.g., mortality or morbidity) that such pollutant concentrations elicit in human beings. They are quantified in units of µg/m3 for particulate matter and parts per billion (ppb) for ozone.

The β coefficients themselves are relative to a percent increase in incidence. For particulate matter, they correspond to the percent increase in the incidence of a response per each 10 µg/m3 change in concentration. For ozone, they correspond to the percent increase in the incidence of a response per each 100 ppb change in concentration. The central estimate of β coefficient values assumed for particulate matter (PM2.5 and PM10) and ozone are summarized in Table 6-2. These coefficients were assumed to remain applicable over the 2007-2035 time period.

Table 4-3: Background pollutant concentration levels (MacDonald Gibson, et al., 2013)

Assumed background pollutant levels, 2008

Value	Pollutant	Units	Estimate
10	PM10	micrograms per cubic meter	Minimum
90	PM10	micrograms per cubic meter	Maximum
50	PM10	micrograms per cubic meter	Average
3.5	PM2.5	micrograms per cubic meter	Minimum
31.5	PM2.5	micrograms per cubic meter	Maximum
17.5	PM2.5	micrograms per cubic meter	Average
0	O3	parts per billion	Minimum
25	O3	parts per billion	Maximum
12.5	O3	parts per billion	Average

Source: Chapter 4 of the UAE Environmental Burden of Disease Assessment
Note: These background pollutnat concentration levels are held constant over the planning period

Table 4-4: Assumed β coefficients, central values (MacDonald Gibson, et al., 2013)

Mortality health outcomes

β, Central Value	Pollutant	Indicator	Units	Exposure type	Health outcome type	Age group
0.08	PM10	Daily average	ug/m3	Short term	All-cause	All
0.166	PM10	Daily average	ug/m3	Short term	Respiratory	<5
0.6	PM2.5	Annual average	ug/m3	Long term	All-cause	>30
0.9	PM2.5	Annual average	ug/m3	Long term	Cardiopuliminary	>30
1.4	PM2.5	Annual average	ug/m3	Long term	Lung cancer	>30
0.052	O3	Daily average	ppb	Short term	Total non-accidental	All

Morbidity health outcomes

β, Central Value	Pollutant	Indicator	Units	Exposure type	Health outcome type	Age group
0.084	PM10	Daily average	ug/m3	Short term	Health care Visits (Respiratory)	All
0.03	PM10	Daily average	ug/m3	Short term	Health care Visits (Cardiovascular	All
0.34	O3	Daily average	ppb	Short term	Health care Visits (Respiratory)	All

4.11 Relative risk

"Relative risk" is a measure of the magnitude of an association between an exposed and non-exposed group. It describes the likelihood of developing disease in an exposed group compared to a non-exposed group. In the EBDA's health model, it is calculated by taking the natural exponent of the product of the concentration-response coefficient and the change in the concentration of a pollutant, as summarized in the formula below.

$$\textit{Relative Risk (RR)} = e^{(\beta * \Delta x)}$$

Where:

β = Concentration-response coefficient from epidemiological studies (% increase in cause-specific mortality or morbidity per 10 µg/m3 for PM or per 100 ppb for O3

Δx = Change in the concentration of the pollutant of interest (i.e., PM10, PM2.5, and O3) in units of µg/m3 for PM and ppb for O3 at the centroid in each of the 462 grid cells in the Abu Dhabi Metropolitan Area.

4.12 Attributable fraction

The "Attributable fraction" is defined as the fraction of a disease burden that is attributable to a risk. In the EBDA, it is calculated by dividing the Relative Risk minus 1 by the total relative risk, as summarized in the formula that follows.

Attributable fraction (AF) = (Relative risk -1) / Relative risk

Where:

Relative risk = the health risk associated with a particular disease burden (see preceding formula

4.13 Baseline incidence rate

The "Baseline incidence rate" is a measure of the frequency of cases of a health endpoint in a population at risk from that health endpoint. In the EBDA, it is calculated by dividing the total incidence of a health endpoint by the applicable population for that health endpoints as summarized in the formula that follows. It is assumed to be constant over time.

Baseline incidence rate (BIR) = health endpoint / population at risk

Where:

Health endpoint = A direct marker of disease progression (e.g., deaths or health-care facility visits) resulting from exposure to environmental or other factors

Population at risk = the total population at risk from the health endpoint

4.14 Abu Dhabi population at risk, 2008

Table 4-5: Assumed population at risk in Abu Dhabi emirate (MacDonald Gibson, et al., 2013)

Approximate population estimate in Abu Dhabi by age group, 2008

Value	
1493000	Total population
708000	Population over 30 years of age
77000	Population under 5 years of age

The "Abu Dhabi population at risk" refers to the total number of people who are subject to outdoor air pollution risks within the Abu Dhabi emirate. In the EBDA, the 2008 values for each emirate were used as the basis for the estimates of premature deaths (i.e., 650 for particulate matter and 77 for ozone) and excess health-care visits (15,000 for particulate matter and 9,800 for ozone) in the UAE due to outdoor air pollution. The Abu Dhabi-specific values assumed in 2008 are summarized in Table 6-3. For the purposes of the co-benefits analysis, the age-specific shares for the Abu Dhabi emirate were assumed to be applicable to the Abu Dhabi Metropolitan Area over the 2007-2035 period.

4.15 Calculation of public health co-benefits

The above assumptions were codified into algorithms in CoMPAD to compute the magnitude of premature deaths avoided and excess health-care facility visits avoided. Co-benefits are generated as pollutant concentrations decrease throughout the Abu Dhabi Metropolitan Area due to the implementation of the GHG mitigation policies. For 2035, the difference in average annual pollutant concentrations is calculated directly on the basis of model-generated ambient air pollutant concentrations. For intervening years, linear scaling and interpolation techniques will be applied to determine the change in ambient air pollutant concentrations from the start year of policy implementation through to the end of the assessment period. The expression below describes the calculation for estimating cumulative public health co-benefits for a given impact category.

$$(CoB)_{i,t} = \sum_{g=1}^{462} \sum_{i=1}^{2} \sum_{p=1}^{2} AF_{ip} * BIR_{ip} * Pop_g * \Delta t/2$$

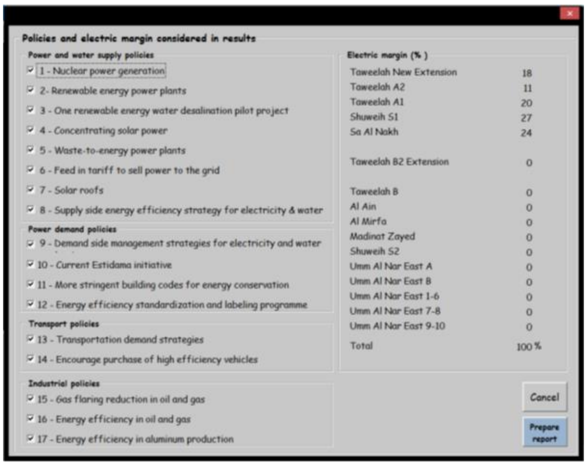
where:

- i = *health endpoint category (i.e., avoided premature deaths; avoided excess health care facility visits*
- p = *pollutants (i.e., particulate matter, ozone)*
- AF_{ip} = *Attributable fraction for health endpoint i, for pollutant p*
- BIR_{ip} = *Baseline incidence rate for health endpoint i, for pollutant p*
- Pop_g = *population in grid cell g in the out year*
- Δt = *Number of years between the start year for GHG mitigation implementation and the year for which co-benefits are being estimated,*
- $CoB_{i,t}$ = *Cumulative public health co-benefits for health endpoint category i through year t*

5. Public health co-benefits associated with Abu Dhabi's Climate Change Strategy

This section provides an overview of the results of the public health co-benefits associated with the implementation of Abu Dhabi's Climate Change Strategy. The section begins with a brief overview of essential framing issues. This is followed by a discussion of each of the modeling components used to estimate the magnitude of public health co-benefits accrued from the GHG mitigation policies.

Figure 5-1: Policies included in the estimation of public health co-benefits



5.1 Introductory remarks

The calculation of public health co-benefits is a function of the kinds of policies implemented and the nature of their implementation. That is, some policies affect emissions from point sources (e.g., Policy Option #1: Nuclear power generation) while other policies affect emissions from mobile sources (e.g., Policy Option #14: Encourage purchase of high efficiency vehicles). The kind of policy has a large impact on how pollution is dispersed (i.e., large quantities from a few tall stacks versus small quantities from many ground-level sources). In addition, some policies apply targets that can have a large impact on the particular sector while other policies apply targets that produce a more modest impact. Within CoMPAD, these differences are accounted for by a) assigning explicit values to targets for each policy and b) providing the capability for analyzing a single policy or many policies in combination.

The results presented in this section are based on an illustrative CoMPAD run assuming that all policies are implemented. It is important to emphasize that the results are illustrative as they are based on target assumptions that may or may not be consistent with actual plans. Moreover, they are based on default data assumptions that may not adequately represent actual conditions. Nevertheless, the results offer a window into the orders of magnitude regarding what the Climate Change Strategy might achieve relative to emission reductions, air quality benefits, and public health co-benefits. The results on a per policy basis are contained within the CoMPAD model itself.

5.2 Policies analyzed

As noted above, all policies in Abu Dhabi's Climate Change Strategy were assumed to be implemented over the 2015-2035 period. Figure 7-1 shows a screen capture of CoMPAD that indicates that all policies were selected for analysis.

5.3 Policy Targets

As much as possible, targets were established consistent with information provided in the Climate Change Strategy, where such information was available. For those policies where targets are in the process of being developed and hence unavailable, placeholders assumptions were made. These assumptions were typically on the aggressive side, as a way of illustrating the public health potential. They should not be understood as a prediction of the eventual target, but simply a placeholder until such targets are finalized. The bullets below summarize the target assumptions.

- *1: Nuclear power generation* – 4 units each with a net capacity of 1,345 MWe, coming only in 2017, 2018, 2019, and 2020.
- *2: Renewable energy power plants* – Start year for the policy in 2020, with 10% of all generation comes from non GHG-emitting renewable sources by 2035.
- *3: One renewable energy water desalination pilot project* - Start year for the policy is 2020 for a 100 MW solar PV station.
- *4: Renewable energy water desalination plants* - Start year for the policy is 2020 for a 100 MW concentrating solar power stations (Shams 1) and a 10 MW concentrating solar power stations (Masdar).
- *5: Waste-to-energy power plants:* Start year for the policy is 2020 for a 50 MW waste-to-energy plant.
- *6: Feed in tariff to sell power to the grid* - Start year for the policy in 2020, with the feed-in tariff leading to an incremental 10% of all generation comes from non GHG-emitting renewable sources by 2035.
- *7: Solar roofs* - Start year for the policy in 2020, resulting in 10% of all generation coming from distributed generation in solar roofs by 2035.
- *8: Supply side energy efficiency strategy for electricity and water production* - Start year for the policy in 2020, resulting in 1.0%/year improvement through 2035 in the heat rate (i.e., combustion efficiency) of the following power stations: Taweelah New Extension, Taweelah A2, Shuweih S1, and Sas Al Nakhi.
- *9: Demand side management strategies for electricity and water production* - Start year for the policy in 2020, resulting in 10% demand side savings in new residential construction by 2035.
- *10: Current Estidama initiative* - Start year for the policy in 2020, with 10% electricity savings of new commercial buildings by 2035.
- *11: More stringent building codes for energy conservation* - Start year for the policy in 2020, with 10% of new home floor space included in the Progamme by 2035.
- *12: Energy efficiency standardization and labeling programme* - Start year for the policy in 2020, with 10% electricity savings in the residential sector by 2035.

- *13: Transportation demand strategies* - Start year for the policy in 2020, with passenger car and passenger light vehicle kilometer growth rates half of what they were in the Baseline Scenario.
- *14: Encourage purchase of high efficiency vehicles* - Start year for the policy in 2020, with all passenger vehicles a 50%-50% mix of plug-in hybrid and electric vehicles by 2035 and all other vehicle sales being 100% high efficient vehicles by 2035.
- *15: Gas flaring reduction in oil and gas industry* - Start year for the policy in 2020, with flaring growth rates half of what they were in the Baseline Scenario.
- *16: Energy efficiency at industrial cogeneration facilities* - Start year for the policy in 2020, resulting in 1.0%/year improvement through 2035 in the heat rate of the following facilities: Asab Agd II, Ruwais refinery, Habshan, Bu Hasa Adgas, Al Wagan, Sheikh Khalifa hospital, Mussafeah Industrial City.
- *17: Energy efficiency in aluminum production* - Start year for the policy in 2020, resulting in 1.0%/year improvement through 2035 in the heat rate of the Taweelah aluminum smelter.

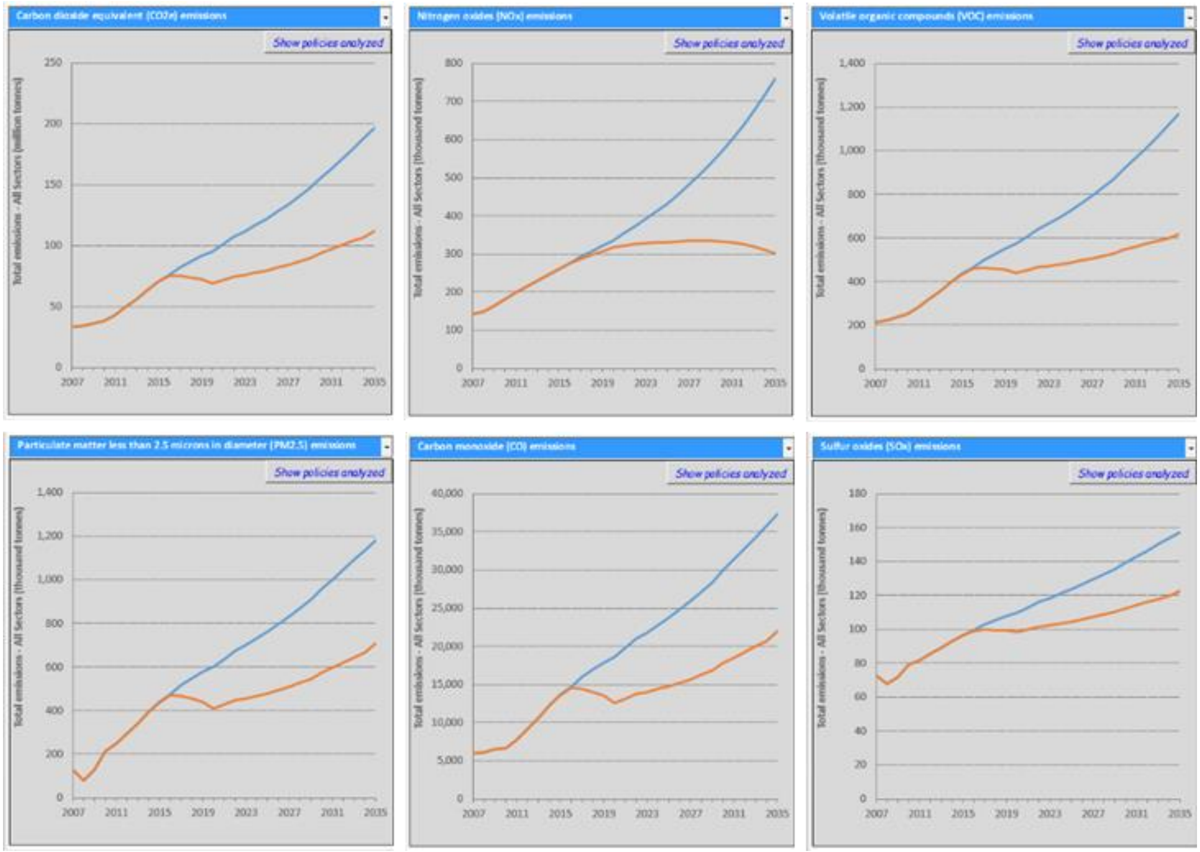
5.4 Emission reductions

The emissions trajectories associated with the implementation of all policies in shown in Figure 7-2. As shown in the Figure, the collective impact of the Climate Change Strategy is significant, resulting in a sharp decrease in the average annual rate of growth in emissions. Relative to Baseline Scenario emissions in 2035, the reductions achieved by the policies range from 40% for PM2.5 to 60% for NOX. The sharp discontinuity in the charts for all but NOx reflect the impact of the nuclear station coming online and the emission factor assumptions that were used to compute total emissions.

5.5 Changes in air quality

The air quality changes in 2035 associated with the implementation of all policies in shown in the maps in Figure 7-3. As shown in the Figure, the collective impact of the Climate Change Strategy is significant, resulting in a improvements in air quality, especially around the location of stationary sources of pollution. Though not reported here, air quality changes are also estimated for the intervening years of 2020, 2025, and 2030. It is important to note that only changes in PM2.5 and O3 concentrations are used to estimate public health co-benefits. For fine particulate matter, most of the Abu Dhabi Metropolitan Area (i.e., 332 out of 462 grid cells, or 72%) experiences improvements in air quality less than 30 µg/m3. For those areas close to large stationary sources of pollution air quality changes can be many times higher. For ozone, the situation is similar. Most of the Abu Dhabi Metropolitan Area (i.e., 430 out of 462 grid cells, or 93%) experiences improvements in air quality less than 30 µg/m3.

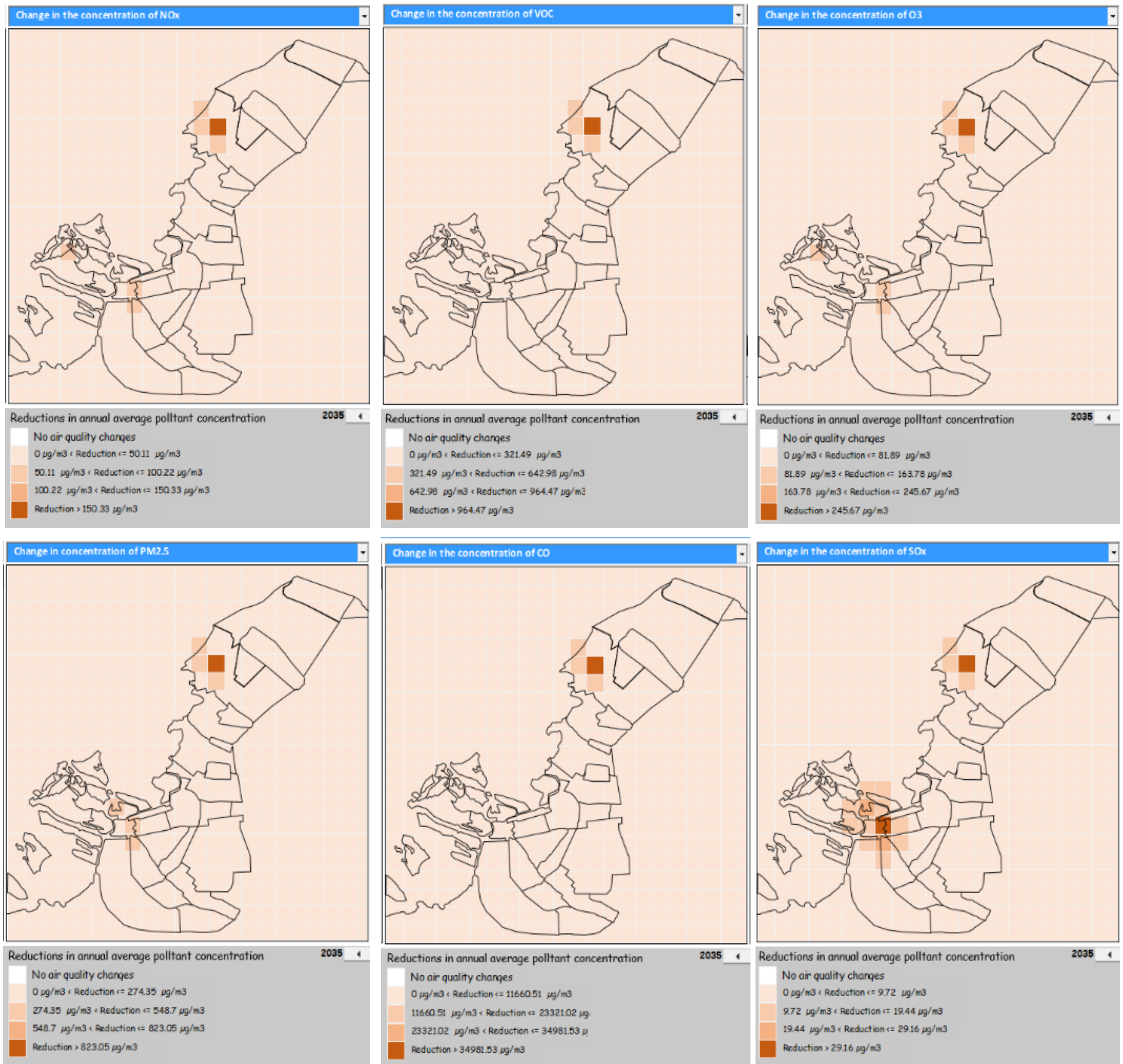
Figure 5-2: Emissions trajectories in the Baseline and All Policy scenarios, 2007-2035



5.6 Premature deaths avoided

The annual premature deaths avoided in 2035 and cumulative premature deaths avoided through 2035 due to the implementation of all policies in shown in the maps in Figure 7-4. As shown in the Figure, the collective benefits to public health in the Abu Dhabi Metropolitan Area from the implementation of the Climate Change Strategy is significant, resulting in 2,896 cumulative avoided premature deaths from particulate matter and 313 cumulative avoided premature deaths from ground-level ozone. In total, 3,219 premature deaths are estimated to be avoided by the implementation of the Climate Change Strategy. For particulate matter, the areas showing the highest benefits from implementation of the policies are located near Abu Dhabi Island and the Capital District. For ozone, the areas showing the highest benefits from implementation of the policies are located near Abu Dhabi Island. Though not reported here, premature death avoided are also estimated for the intervening years of 2020, 2025, and 2030.

Figure 5-3: Air quality changes by grid cell associated with the implementation of all policies, 2035



5.7 Excess health-care facilities avoided

The annual excess health-care visits avoided in 2035 and cumulative excess health-care visits avoided through 2035 due to the implementation of all policies in shown in the maps in Figure 7-5. As shown in the Figure, the collective benefits to public health in the Abu Dhabi Metropolitan Area from the implementation of the Climate Change Strategy is significant, resulting in 40,769 cumulative avoided excess health-care facility visits due to exposure to particulate matter and another 42,084 cumulative avoided excess health-care facility visits due to exposure to ground-level ozone. In total, 82,853 avoided excess health-care facility visits are estimated to be avoided by the implementation of the Climate Change Strategy. For particulate matter, the areas showing the highest benefits from implementation of the policies are located near the Capital District. For ozone, the areas showing the highest benefits from implementation of the policies are located near Abu Dhabi Island. Though not reported here, excess health-care facility visits avoided are also estimated for the intervening years of 2020, 2025, and 2030.

Figure 5-4: Avoided premature deaths by grid cell associated with the implementation of all policies, 2035

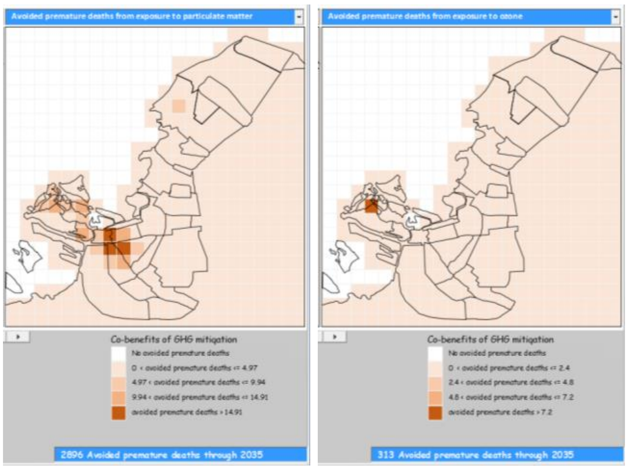
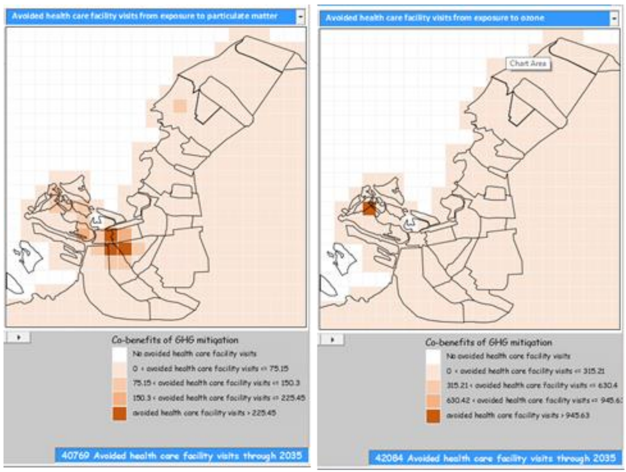


Figure 5-5: Avoided excess health-care facility visits by grid cell associated with the implementation of all policies, 2035



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