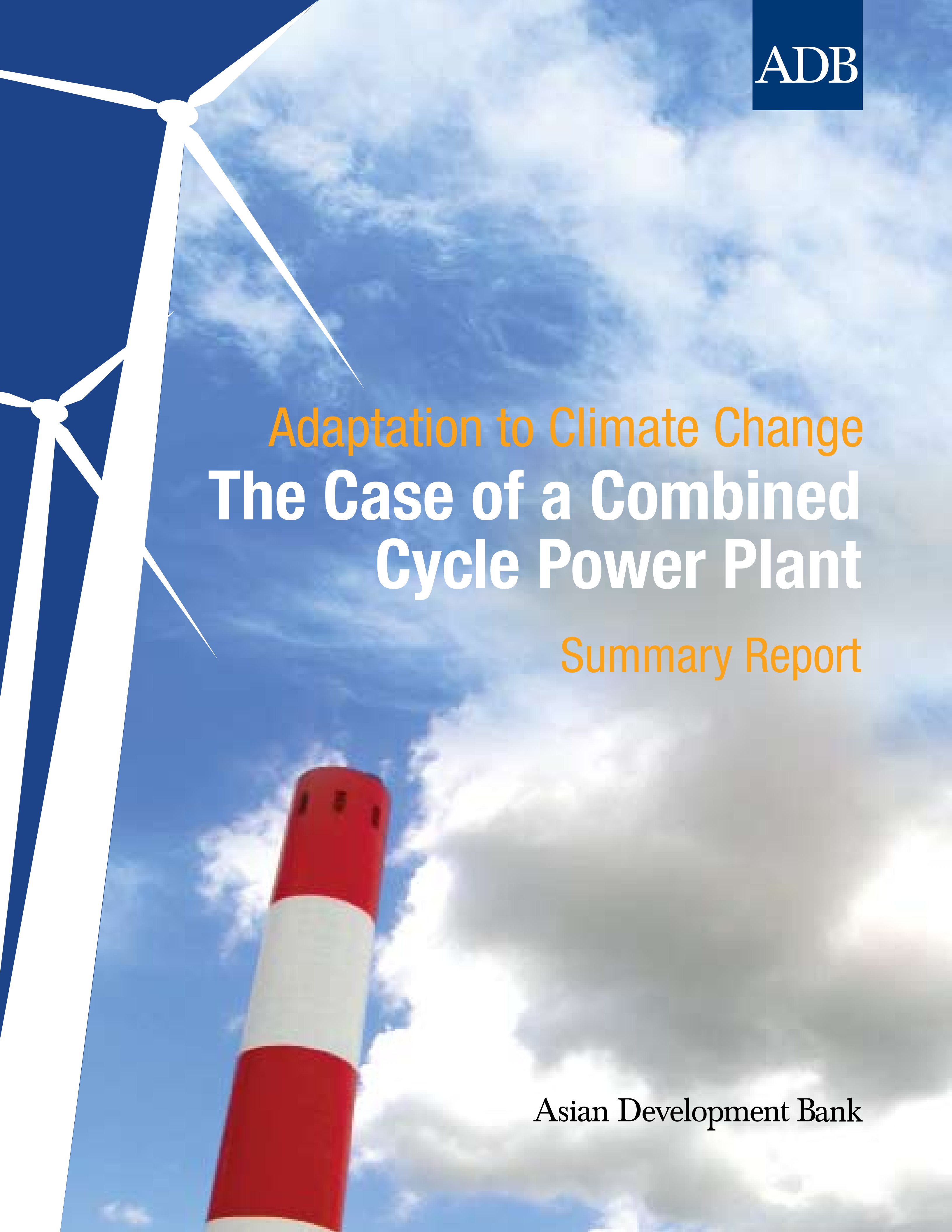

ADB

Adaptation to Climate Change

The Case of a Combined Cycle Power Plant

Summary Report

Asian Development Bank

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The Case of a Combined Cycle Power Plant

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Foreword

Many of the projected impacts of climate change are likely to adversely affect critical infrastructure assets within the region. ADB is committed to helping its developing member countries to better understand the risks posed by climate change and to manage these risks effectively. To this end, ADB is developing a suite of tools, resources, and guidance materials to support comprehensive, rapid, and cost-effective climate risk management at sector and project levels. These resources include preliminary rapid risk screening tools, improved access to climate change projections, technical notes providing guidance for climate proofing investments in critical development sectors, and case studies illustrating approaches to climate risk assessment and identifying appropriate and promising adaptation responses.

This publication is an important contribution to the case study literature on adaptation. The energy sector is potentially among the most vulnerable to projected changes in climate variables, and this report illustrates the use of a rapid climate impact assessment to assess how climate change is likely to influence the performance of a thermal power plant. This report uses the O Mon IV combined cycle power station project in southern Viet Nam as a case study. It also discusses a number of adaptation options that the project may utilize to address the potential impacts of climate change.

The production of this publication would not have been possible without the support of the governments of Japan and the United Kingdom through the regional technical assistance project Promoting Climate Change Adaptation in Asia and the Pacific (RETA 6420). This report was prepared by Benoit Laplante on the basis of the report *O Mon IV Power Station: Rapid Climate Change Threat and Vulnerability Assessment*, prepared by the International Centre for Environmental Management (ICEM) under RETA 6420. The ICEM study team comprised Jeremy Carew-Reid, Tarek Ketelsen, Jorma Koponen, Nguyen Quoc Khanh, Nguyen Huu Nhan and Tranh Thanh Cong.

We would also like to acknowledge the guidance provided by Ayumi Konishi, ADB country director for Viet Nam, in the conduct of the study. It was coordinated and supervised by James Roop, senior environment specialist (Pacific Department), and Charles Rodgers, senior climate change specialist (Environment and Safeguards Division). Lorie Rufo, environment officer (Environment and Safeguards Division), provided technical assistance and overall support. Valuable comments were provided on earlier versions of the report by Anil Terway, ADB senior advisor and practice leader (energy), Pradeep Tharakan, climate change specialist (Southeast Asia Department), and Karen Freund (KfW).

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Abbreviations

ADB	Asian Development Bank
CCAM	climate change adaptation and mitigation methodology
CCGT	combined cycle gas turbine
CSAG	Climate Systems Analysis Group
GCM	general circulation (or global climate) model
GWh	gigawatt hour
HRSG	heat recovery steam generators
ICEM	International Centre for Environmental Management
km	kilometer
kWh	kilowatt hour
m^3	cubic meter
masl	meters above sea level
MW	megawatt
PECC3	Power Engineering and Consulting Company No. 3

Executive Summary

Although most of the electricity in the Asia and Pacific region is produced from conventional thermal electricity sources (up to 82% of the fuel mix in electricity generation in the region is conventional thermal), the impacts of climate change on thermal power generation have thus far attracted very limited attention.

Climate change may have significant impacts on the generation of electricity, including from thermal power plants. It may do so by causing damage to plant infrastructure, reducing water availability, and increasing air and water temperature.

Higher air temperatures may reduce the power generation efficiency of thermal power plants, leading to a reduction of power generation. Furthermore, an increase in water temperature may adversely impact the operation of the cooling systems of thermal power plants.

The key objective of this report is to demonstrate how a rapid climate change impact assessment can be used to identify the possible impacts of climate change on a thermal power investment project. For this demonstration, the recently approved O Mon IV combined cycle power station project in southern Viet Nam (approved in November 2011) is used for illustrative purposes.

O Mon IV is a combined cycle gas turbine thermal power station with a design capacity of 750 megawatts. Under normal conditions, the plant has a net efficiency of 56.4% and is expected to generate 4,500 gigawatt hours (GWh) of electricity per year. Construction is scheduled to begin in 2013, with the plant expected to come online in the fourth quarter of 2015. Capital cost is estimated to be $778 million.

Five climate-related threats have been identified as being of potential significance. The nature of the exposure and impacts of these threats varies. Some, like air and river water temperatures, threaten day-to-day performance of plant operations, while heavy precipitation and flooding can affect maintenance schedules and downtime. Erosion and flooding could potentially cause damage to planned infrastructure.

Direct climate threat		Potential sensitivity of a power plant
Air temperature	→	Gas turbine cycle performance
River water temperature	→	Steam turbine cycle + coolant water cycle performance
Direct precipitation	→	Performance of gravity-driven stormwater management
Flood depth + Duration	→	Asset damage + plant downtime
Erosion	→	Asset damage

The most significant potential climate change threats are rising air and river water temperatures. While the historic average annual ambient air temperature is 26.7°C at Can Tho, it is projected to rise by 2.8°C to 3.4°C over the period 2045–2065. As for water temperature, it is projected that the proportion of the year when river water temperature is at or above the design temperature of 29.2°C will significantly increase.

The components most vulnerable to reduced performance are the gas and steam turbines, the air compressors, and the circulating water pumps. Most other components are expected to have minor vulnerability to climate change. Asset damage (possibly resulting from river bank erosion and floods) is not projected to be of significance.

Within the context of Viet Nam's official emissions scenario, the study shows that the O Mon IV power plant, as currently designed, may experience an aggregate loss in power output of approximately 827.5 GW as a result of projected increases in air and water temperature over the period 2015–2040. This corresponds to approximately 0.8% of its total design power output over that same period. In addition, the reduction in net efficiency will result in a relative increase in fuel consumption. In present value terms, the loss of power output and increased fuel consumption are estimated to cost approximately $11.0 million over the period 2015–2040. These numbers, in the context of the O Mon IV power plant, remain relatively small. It shall not be presumed that similar results would apply to other power plants in the country or region.

Adaptation responses examined in the study include the following:

- **Improving performance of the gas turbine cycle:** Adaptation options are focused on the gas turbine technology and revolve around either pretreatment of the intake air to reduce temperature or redesigning the topping cycle technology to accommodate a warming climate.
- **Improving performance of the cooling water cycle:** Adaptation options are focused on reducing the intake water temperature or increasing the performance of the cooling water system pumps and heat exchangers.
- **Improving management of the coolant discharge:** Adaptation options are focused on reducing the proportion of coolant feedback at the water intake structures and improving mixing of the coolant plume in the Hau River water column

The analysis reveals that in order not to violate existing environmental standards in Viet Nam and to avoid adverse impacts on power generation, retrofitting with additional equipment (such as a cooling tower) may be required in the future, assuming that actual temperatures fall within the range of current projections. Such retrofitting will require that space be available near the power plant for the installation of the equipment. Hence, while such an investment may be postponed, it may be appropriate to ensure that the needed space will be available if indeed such investment were to prove necessary. Adaptation approaches of this nature have been referred as "climate readiness," indicating that while climate proofing may not be recommended today, a cost-effective course of action may be to ensure that the investment (the project) is ready for adaptation in the future.

Introduction

Most of the electricity produced in the Asia and Pacific region is from conventional thermal electricity sources. In 2007, these sources—including coal, oil, and natural gas—amounted to 82% of the fuel mix in electricity generation, of which coal represents the largest single share (Energy and Resources Institute 2009).

In response to increasing demand for energy, total electricity generation in the region is projected to more than double in the coming 2 decades, increasing from 6,068 terawatt-hours in 2005 to approximately 14,000 in 2030 (ADB 2009).

Despite projected investments in alternative power generation sources (including renewable sources), thermal power will continue to represent the primary source of electricity in the region for the foreseeable future. For developing member countries of the Asian Development Bank (ADB), coal, oil, and natural gas will continue to represent more than 70% of the energy mix. Coal is projected to maintain the largest share, at approximately 55% of the electricity generation mix in developing member countries. In East Asia and South Asia, coal's share of the energy mix is projected to remain above 60% in 2030.

Climate change is expected to have a wide range of impacts on the electricity generation industry.

To date, the potential impacts of rising temperature on electricity demand have attracted most of the attention.[1] However, there is an increasing recognition that climate change may have significant impacts on the generation of electricity by thermal power plants.[2] It may do so by reducing water availability, as well as increasing air and water temperature.

Thermoelectric generation is water intensive. It is estimated that on average, each kilowatt hour (kWh) of electricity generated via steam cycles requires approximately 0.95 cubic meters (m^3) of water.[3] Climate change may impact water availability in numerous ways, including the following:

[1] See for example Amato et al. (2005), Considine (2000), and Franco and Sanstad (2006).

[2] Florke et al. (2011), Forster and Lilliestam (2010), Kopytkoa and Perkins (2011), Mideksa and Kallbekken (2010), and Rubbelke and Vogele (2011).

[3] Approximately 43% of the water withdrawn in the European Union is used as cooling water by power authorities (EUREAU 2009). In the United States, water demand by thermal and nuclear power plants is estimated to be of the same order as water demand in the irrigation sector (Bull et al. 2007). Thermoelectric power generation water withdrawals were estimated to be 201 billion gallons per day in 2005 (or approximately 760 million cubic meters per day) and accounted for 41% of all freshwater withdrawals. Almost all water withdrawal was surface water used for once-through cooling at power plants (Kenny et al. 2009).

- Changes in precipitation patterns may impact the hydrological cycle, including river runoff.
- The retreat of glaciers may increase river discharge over the next several decades followed later by significant reductions in summer flows as glaciers disappear.
- Changes in water use patterns and increasing water demand from sectors other than the power sector may reduce water availability to the power sector.

Simultaneously, changes in air and water temperature may impact power generation efficiency in various ways:

- Higher air temperatures reduce the power generation efficiency of thermal power plants leading to a reduction of power generation. If experienced during heat waves, this reduction may coincide with peak demand; and
- An increase in water temperature may adversely impact the operation of the cooling system of thermal and nuclear power plants.

Changes in the hydrometeorological regime may change flood regimes and increase flood levels at the plant. This in turn may also pose threats to the integrity of plant infrastructure and damage to plant assets.

This report is the outcome of a rapid impact assessment undertaken to assist the Can Tho Thermal Power Company (CTTP) and ADB to integrate climate change into the design and operation of the proposed O Mon IV power station. It is hoped that the methodological approach and findings originating from this rapid impact assessment will be of interest to other thermal power plant investment projects in the region.

O Mon IV is expected to be operational in 2015, with a planned economic design life of 25 years. The station represents a $778 million dollar investment and is part of a five-phase power development complex servicing Can Tho and the Long An, Tien Giang, Vinh Long, and Dong Thap provinces in southern Viet Nam. The O Mon complex will provide 17.5 billion kWh of energy annually, equal to roughly 4% of the projected national demand by 2030 (Power Engineering and Consulting Company No. 3 [PECC3] 2009).

In a large number of instances, power stations in the region continue to be designed with the assumption that average and extreme conditions observed to date will continue throughout the design life of the plant (Biggs et al. 2008). As the threat and impact of climate change become better understood, it is increasingly clear that the assumption of a stationary climate must be questioned. In a warming climate, engineers and urban planners must acknowledge that the design of critical infrastructure should better reflect an increasingly dynamic and uncertain future. In particular, it should (i) determine which climate change threats pose tangible risks to the integrity, efficiency, or output of future investments; (ii) identify the nature of possible adaptation responses; and (iii) assess the technical and economic feasibility of these options, including the appropriate timing of implementation.

During the lifetime of the plant, Can Tho City and the Mekong Delta are projected to experience significant changes in climate (Dasgupta et al. 2009 and CTU 2009). Sea levels and ambient temperatures are expected to rise, while rainfall will become more variable. Wet seasons will get wetter, while droughts will occur with greater frequency and severity. Extreme events are likely to become more frequent as storms and cyclones track further south, hitting the Mekong Delta with increasing frequency. Changes in the Mekong Delta's hydrological regime coupled with increased use of groundwater will exacerbate land subsidence issues (Doyle et al. 2010).

The cumulative impacts of these expected threats will result in changes to the hydrometeorological regime that underlies the design parameters selected by the

O Mon IV project engineers during the design and feasibility stages. These impacts include changes in intake air temperatures, river water temperatures, flood levels and flood events, and flow velocities.

In order to understand how these design parameters may change, the O Mon IV rapid climate change threat and vulnerability study has addressed three major questions related to plant operations and assets:

- What are the direct biophysical climate change threats the plant is *exposed* to?
- What are the projected magnitude and duration of this exposure?
- Which operational, management, and infrastructure components of plant design are sensitive to climate change?

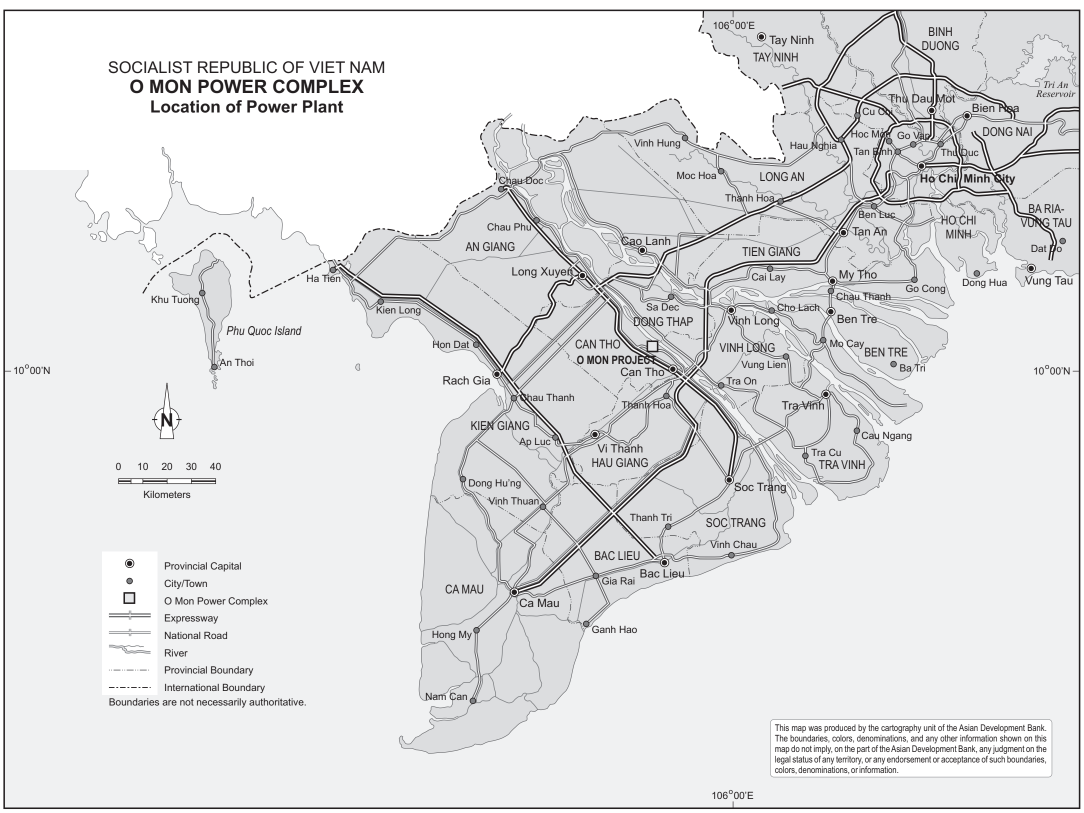
In answering these questions, the study aims to assess the impacts of climate change to the O Mon IV power plant by quantifying the plant's vulnerability, assessing the needs and means for adaptation, and identifying priority areas of response. The use of the O Mon IV project in this report is purely illustrative. The intent of this report is to demonstrate how a rapid assessment may be implemented to assess the potential vulnerability of a power plant investment to climate change. Results and conclusions should therefore be interpreted in this limited context.

The next section provides more details on the O Mon IV power plant and its surrounding environment. Section III describes the methodology used to undertake climate change impact assessment. Adaptation options are discussed in Section IV. Finally, brief conclusions are offered in Section V.

The O Mon IV Power Plant and Its Surrounding Environment

O Mon IV is one of five power plants in the O Mon power complex ("the complex"), which is situated at Phuoc Thoi and Thoi An wards, O Mon district, Can Tho City (Figure 1). The complex lies in the heart of the Mekong Delta on the right bank of the Hau River, approximately 80 kilometers (km) from the coast and 17 km upstream of Can Tho City. This region has complex hydrodynamics, with tidal influences reversing the direction of flow in the river channel and shifting water quality from fresh to brackish. The Mekong's seasonal flood pulse varies water levels by 2.46 meters (m) on average annually, and up to 3.8 m during extreme years.

Figure 1. Location of the O Mon Power Complex

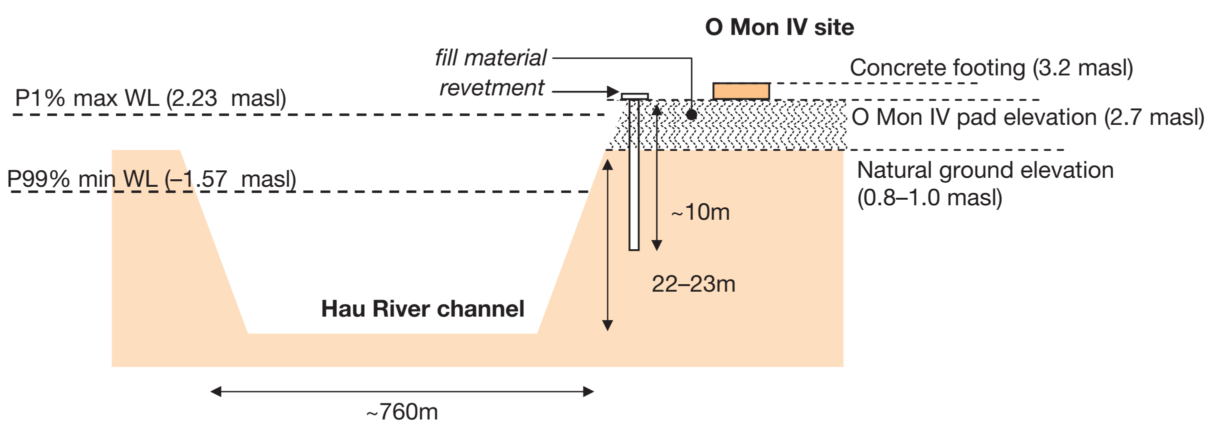


The complex covers an area of approximately 160 hectares of a low-lying island in the Hau River floodplain and is surrounded by the Hau River, the O Mon River, Vam Creek, and Chanh Creek, with a natural ground elevation on average of 0.8–1.0 m above sea level (masl). At the site, the Hau River is a straight channel 760 m wide and 22–23 m in the deepest part, while the two creeks are 6–7 m deep (ADB 2010). Historically, the surrounding land use is predominately agriculture with growing industrial and urban developments.

O Mon IV is a combined cycle gas turbine (CCGT) thermal power station with a design capacity of 750 megawatts (MW). Under design conditions, the plant has a net efficiency of 56.4% and is expected to generate 4,500 gigawatt hours of electricity per year. Fuel supply will come via pipeline from gas fields in the Gulf of Thailand. Construction is scheduled to begin in 2013 with the plant expected to come online in the fourth quarter of 2015.

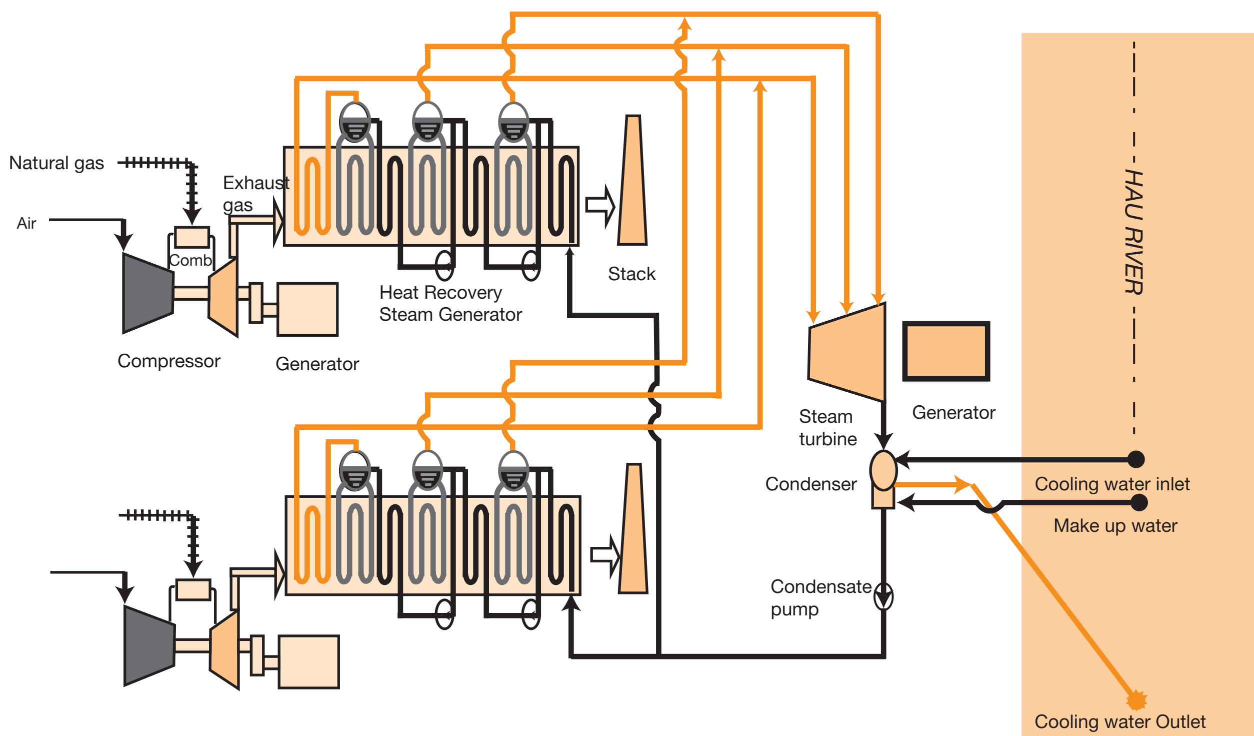
O Mon IV will be built to an elevation of 2.7 masl, which requires that the plant pad be raised by 1.7–1.9 m. The elevation of the plant pad is the primary protection measure against overbank flooding and other riverbank hydraulic processes. In addition, a revetment system will be installed involving interlocking metal sheets sunk 10 m below the surface along the Hau River bank in order to protect the bank from erosion. The barrier is capped with concrete protruding 0.2 m above the elevated pad level. Each major component in the plant also sits on a concrete footing, providing a further 0.5 m freeboard, such that the majority of plant equipment sits at or above 3.2 masl, or approximately 1.0 m above the historic 1-in-100 year return period flood event (Figure 2).

Figure 2. Site Elevation



masl = meters above sea level, WL = water level
Note: P1% indicates a flood level with an annual exceedance probability of 1% or 1–in 100 year flood.
P99% indicates a flood level with an annual exceedance probability of 99%.

Figure 3. Schematic Diagram of the O Mon IV Combined Cycle Plant



CCGT power plants such as O Mon IV use natural gas, oxygen, and water to generate electricity via two key thermal processes—the gas turbine cycle and the steam turbine cycle—both of which convert thermal energy (combustion) into mechanical energy at the turbine and subsequently into electrical energy at the generator (Figure 3). Each process is supported by a cooling process designed to remove heat from the system.

Three processes are critical to power production and directly rely on the surrounding environment (air and water) for inputs.

Gas turbine cycle. In the O Mon IV *topping cycle*, air is drawn from the atmosphere into a compressor and then injected under pressure into the combustion chamber together with natural gas, where it is ignited to produce a high temperature and high-pressure gas. The turbine inlet temperature typically reaches roughly 1200˚C. In the turbine, these gases are then converted to work, which drives the turbine connected to a generator for electricity production. Each gas turbine has a design power output of 260–290 MW and design efficiency in the order of 40%.

Steam turbine cycle. Exhaust gases from the gas turbines remain at very high temperatures (638˚C).The CCGT process recycles the remaining energy in the exhaust gas to drive a secondary or *bottoming* cycle. This is achieved by piping the exhaust gas through a heat recovery steam generator (HRSG) system to heat treated river water for the generation of steam. Under normal operations, 84 m^3/hr of raw water is drawn from the Hau River and undergoes treatment including sedimentation, primary and secondary filtration with activated carbon, and demineralization. The purified water is then passed through the HRSG system and converted into steam by utilizing the heat in the topping cycle exhaust gas. The steam from both HRSGs is forced through the throttle to drive a single steam turbine connected to a generator for electricity production. The steam turbine has a design power output of 264–289 MW and efficiency in the order of 30%.

After the steam expands through the turbine, it is piped through a heat exchanger to convert the steam back into water (condensate). This condensate is then returned to the HRSG through high-pressure feed pumps for reuse.

Cooling water cycle. In order to convert the steam expelled from the turbine back into a condensate, heat must be extracted. In O Mon IV, this is achieved using a once-through cooling water cycle. The source of the cooling water is the Hau River, where water is drawn by gravity into an underground pit via a screened 30-meter-wide intake. Two cooling water pumps with a combined design capacity of 18 m^3/hr then draw water from an inlet 5 m below the surface and pump the cooling water into the heat exchanger. The external surface of the heat exchanger is exposed to pumped cooling water, while the expelled steam flows within. This transfers heat energy from the steam flowing inside the pipes to the cooling water outside, cooling the steam back to water.

The cooling water exits the heat exchanger at a higher temperature than the inlet and is circulated to an underground tank before being discharged back to the Hau River via an open channel. The increase in temperature (between the inlet and the discharge) can be controlled by altering the pumped flow rate by partially opening or closing the globe valves immediately downstream of the cooling water pumps. A higher flow rate will result in lower discharge temperature for the cooling water but will require greater fuel consumption at the cooling water pumps. Under normal operating conditions the valves are 70%–80% open, with total energy consumption in the cooling water pumps of 4,114 kilowatts and

Table 1. Projected Hydropower Development in the Mekong Basin*

Mekong Basin Country	No. of Dams		Total active storage (mcm)		Total installed capacity (MW)	
	2000	2015	2000	2015	2000	2015
Lao PDR	8	20	5,593	17,166	621	3,502
Thailand	6	6	3,276	3,276	245	245
Cambodia	0	1	0	0.12	0	1
Viet Nam	1	13	779	2,619	720	2,284
PRC	1	6	257	23,193	1,550	15,450
TOTAL	**16**	**46**	**9,905**	**46,254**	**3,136**	**21,482**

m^3 = cubic meters, MW = megawatt, Lao PDR = Lao People's Democratic Republic, PRC = People's Republic of China.

Source: Mekong River Commission (MRC). 2010. Evaluation of the Basin-wide Development Scenarios, Basin Development Programme Phase 2, Vientiane, Lao PDR.

* Projected values for 2015 were estimated by the Mekong River Commission's Basin Development Program (BDP) in 2009 based on consultation with the Mekong countries (the "definite future" scenario). The scenario does not include hydropower projects which have subequently been approved - for example the Lower Sesan 2 Hydropower Project in Cambodia

a discharge temperature less than 7°C above the natural river water temperature.

These three processes are influenced by the range and average daily temperatures of the working media—air and river water.

In the past 15 years the Mekong Basin has been undergoing significant changes as the Mekong countries of Cambodia, the Lao People's Democratic Republic (PDR), Thailand, Viet Nam, and the People's Republic of China (Yunnan Province) seek to develop the basin's immense potential for hydropower. By 2015, the number of hydropower projects on the Mekong River and its tributaries will increase from 16 to 46, increasing installed capacity from 3,136 MW to 21,482 MW (Table 1). These 46 projects will have the capacity to store 46,254 million m^3 of wet season flow in their reservoirs for release during dry season for electricity production. With an average annual flow of 495,000 million m^3, this represents the capacity to store in the order of 10% of wet season flows, resulting in an average 20%–50% increase in dry season flows at Kratie.

An assessment of the future flow and water levels in the Hau River at O Mon IV by 2040 needs to incorporate this regulation of seasonal flows in the basin and loss of sediment load.

While the original study prepared by the International Centre for Environmental Management (ICEM 2011) includes an assessment of the possible impacts of these changes in water flows, this report focuses solely on the impacts of projected changes in air and water temperature. It is shown that these projected alterations in flow are likely to have a minimal impact on power generation at O Mon IV.

Assessment Methodology

In designing and building large infrastructure projects, investors and engineers utilize safety margins to factor an acceptable level of risk into project design—freeboards are included in flood protection works, ranges of variability are built into operating processes, and performance curves are developed for particular infrastructure components. This characterization of risk is fundamental to plant management as it aims to achieve an appropriate balance between ensuring a desired level of safety, optimizing performance, and minimizing the cost of investment. Generally, larger safety margins will entail larger cost. Methods such as hydroeconomic analysis and composite risk analysis are used to optimize the capital cost and the risk of failure from extreme events, forecast the current and future demand on plant infrastructure, and define plant capacity within the acceptable level of risk (Chow et al. 1988).[4]

The characterization of risk for large infrastructure relies on detailed statistical analysis of historic time-series data to understand relevant hydrogeophysical conditions and set key design parameters (such as ambient temperature, maximum water levels, and earthquake incidence). In the long term, some of these parameters may change in response to climate change—affecting the performance of the plant, the cost of maintenance, and the life of plant components.

The rapid assessment methodology utilized in this study adapts the ICEM climate change adaptation and mitigation methodology (CCAM) to characterize the threat, assess the plant's vulnerability, and recommend priority areas for adaptation response to climate change over the plant's design life. At the core of this approach are four key principles:

- **Confidence in impact.** Direct threats are those that inform a key design parameter of the plant and for which changes in trends for that parameter can be quantified with confidence. The concept of *directness* is an important element of the methodology to reduce the level of uncertainty that the climate change analysis introduces into the design.
- **Identification of uncertainty.** Acknowledging the uncertainty in projected climatic conditions

[4] Hydroeconomic analysis estimates the damage and probability of occurrence associated with a particular hydrologic event and uses this information to optimize the design return period against the capital cost of infrastructure. Composite risk analysis accounts for the risks that arise from multiple sources of uncertainty by fitting probability distributions to plant loading and capacity and estimating the likelihood of loading exceeding capacity.

can improve understanding of likely exposure and build confidence in assessment findings. In this study, the methodology utilizes two future climate scenarios developed by the Intergovernmental Panel on Climate Change, namely the *Special Report on Emissions Scenarios* A2 and B2 (IPCC 2000) and the outputs of eight different general circulation models (GCM) to explore a range of impacts based on the range of threats identified by international scientific consensus. Where necessary, reporting has followed these ranges to better characterize threats.

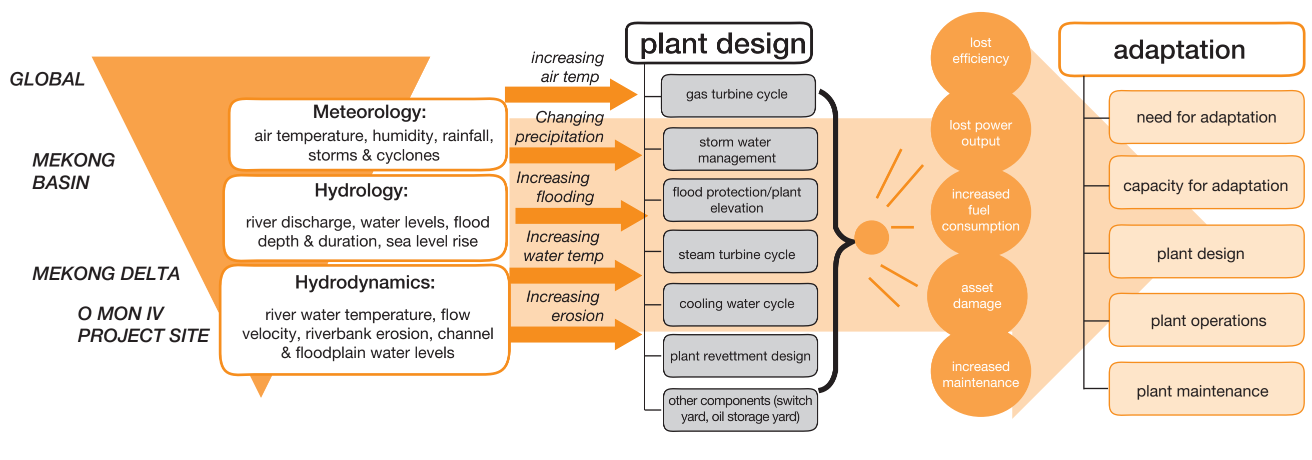
- **Comparable methodology.** Where possible, similar methodologies are employed in the study as those used by design engineers to set the design parameters. This allows results to be compared with calculations undertaken during conventional design phases.
- **Phasing response.** The impacts of climate change on a power plant may extend over the entire plant life. Some adaptation measures may be required or are best implemented at the design phase. Other measures may be introduced at a later time. To this extent, adapting to climate change involves not only selecting adaptation measures, but also identifying the timing of implementation of these measures.

Figure 4 outlines the conceptual approach to this climate change assessment.

A. Approach to Threat Analysis

Figure 5 details specific components of the assessment methodology. The main objective of the threat analysis is to define and quantify the changes in spatial–temporal dimensions of climate variability. This includes the changes in incidence, magnitude, and duration of hydrometeorological events. The threat analysis uses modeling to downscale GCM projections of future climate and then projects changes in the hydrological regime given projected future climate. Eight GCMs and two different

Figure 4. Conceptual Framework of the Climate Change Rapid Threat and Vulnerability Assessment



downscaling techniques (dynamical and statistical) were used. The ICEM integrated water resource management model was then used to incorporate climate change into the Mekong Basin hydrological regime and establish the boundary conditions at Kratie.

The next phase in the modeling was to determine the delta-wide changes in flooding downstream of Kratie using the boundary conditions provided by the ICEM integrated water resource management model and the predictions for sea level rise defined in the official scenario of the Government of Viet Nam. This modeling utilized a hydrogeographic information system developed by the Ministry of Natural Resources and Environment. It presents a picture of future regional changes to flood duration and depths for the delta and defines the water level and discharge boundary conditions for the next phase of detailed hydrodynamic modeling.

The final modeling activity was the development of a detailed three-dimensional model of the channel network surrounding O Mon IV including the Hau and O Mon rivers, as well as the Vam Cong and O Mon complex discharge canals and the surrounding floodplains. This phase modelled (i) heat exchange at the air–water interface to predict changes in the river water temperature profile at the O Mon IV inlet structures, (ii) changes in flow velocity and erosion potential, and (iii) water levels of the Hau River and surrounding canals under climate change. Importantly, the hydrodynamic modeling also incorporated an assessment of the potential of the coolant feedback loop from the plant discharge channels to "blow back" and exacerbate increasing river water temperatures at the inlet site.

Lastly, the threat analysis assessed future changes in the Mekong hydrological regime due to intensified upstream hydropower and irrigation development to quantify their impacts during the design life of the project.

B. Approach to Vulnerability Analysis

The vulnerability assessment combined aspects of conventional engineering feasibility assessments with life cycle analysis. It relied on two assessment phases: (i) the sensitivity of the plant design to climate variability and (ii) the combination of the quantified direct threat and plant sensitivity to determine the impact over the design life.

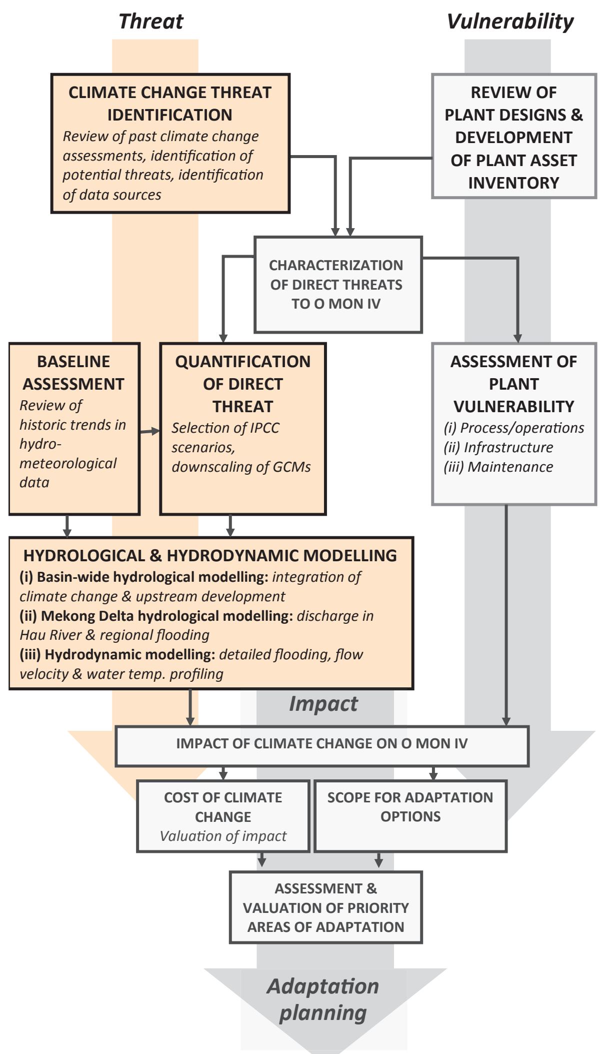
First, an assessment was made of the hydrophysical conditions of the O Mon IV site with a focus on bank stability, geomorphic conditions of the immediate channel reach, and pad elevation/stability. A detailed assessment was then made of the plant design by reviewing plant design parameters and identifying potentially vulnerable processes and components of the plant. An infrastructure inventory was compiled to determine the physical assets most at risk of damage and their value. Then an assessment was made of all plant processes to identify those that may be enhanced or compromised by climate change. This defined the sensitivity of the plant design to the threats of climate change. Functional links were then established between the vulnerable processes and assets, and the direct threats were identified during the threat analysis phase.

The impact analysis overlaid each climate change threat projected by the modeling on the vulnerability of specific plant components, using identified functional links. Based on these relationships, an assessment was then made on the magnitude of the climate change impact over the design life, quantifying the scale of the risk posed by climate change to the design and the level of climate change response needed.

C. Approach to Adaptation Scoping

Once the magnitude of the impact and the need for adaptation were understood, a rapid assessment was made of the adaptive capacity of the plant's design, and priority areas of response were identified along with a number of corresponding potential adaptation options. These adaptation options are intended to establish the framework for comprehensive adaptation planning.

Figure 5. Schematic Representation of Critical Steps in the Assessment Methodology



GCM = general circulation model, IPCC = Intergovernmental Panel on Climate Change

Assessing Vulnerability To Climate Change

As show in Figure 6, five potential threats were identified as being of greatest significance.

The nature of exposure and impact of these threats varies. Some, like air and river water temperature, threaten day-to-day performance of plant operations, while precipitation and flooding can affect maintenance schedules and downtime. Erosion and flooding were identified as the two potential threats that could damage planned infrastructure.

Following the CCAM methodology, direct threats were characterized and linked to associated plant components or processes. In this way, the vulnerability of the plant is specific to the prevailing hydrophysical environment of the site and the specific parameters and design specifications. Unless stated otherwise, details of plant design were obtained from Can Tho Thermal Power Company, the Power Engineering and Consulting Company No. 3 (PECC3), and the field mission.

Figure 6. Potential Threats

Direct climate threat		Potential sensitivity of a power plant
Air temperature	→	Gas turbine cycle performance
River water temperature	→	Steam turbine cycle + coolant water cycle performance
Direct precipitation	→	Performance of gravity-driven stormwater management
Flood depth + Duration	→	Asset damage + plant downtime
Erosion	→	Asset damage

This section focuses on assessing the vulnerability of the power station to changes in air and river water temperature.

A. Changes in Air Temperature

1. Quantifying Future Air Temperature

In order to develop future climate scenarios at Can Tho, the results of eight GCMs were used to generate projections for two different time slices (2036–2045 and 2045–2065) and for two different emissions scenarios (A2 and B2) from the Intergovernmental Panel on Climate Change (Table 2). Two downscaling techniques (statistical and dynamical) were utilized in order to evaluate the influence of the downscaling methodology on the results.[5] Results from a dynamical downscaling model with a full description of atmospheric physics were obtained from the Southeast Asia Global Change System for Analysis, Research and Training Centre using the PRECIS platform, while results from a statistical downscaling approach were obtained from the Climate Systems

[5] See Wilby and Wigley 1997, Wilby et al. 1998, Wood et al. 2004, and Wilby and Fowler 2011 for details on downscaling techniques.

Table 2: Key Features of the Climate Modeling Approach

General Circulation Model ID	GCM Source	Downscaling Methodology	Source of Downscaled Data	Baseline Time-Slice	Future Time-Slice	IPCC SRES Scenario
ccma_cgcm3_1	Canadian Centre for Climate Modeling and Analysis	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
cnrm_cm3	Meteo-France, Centre National de Recherches Meteorologiques	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
csiro_mk3_0		Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
csiro_mk3_5	Australian Commonwealth Scientific & Industrial Research Organisation	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
gfdl_cm2_0	NOAA Geophysical Fluid Dynamics Laboratory	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
giss_model_e_r	NASA Goddard Institute for Space Studies	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
ipsl_cm4	Institut Pierre Simon Laplace	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
mpi_echam5	Max Planck Institute of Meteorology (Germany)	Statistical/ empirical	CSAG	1961–2000	2045–2065 (Future A)	A2
		PRECIS (dynamic)	SEA START	1980–2000	2036–2045	A2, B2

CSAG = Climate Systems Analysis Group, GCM = general circulation model, IPCC = Intergovernmental Panel on Climate Change, NOAA = U.S. National Oceanic and Atmospheric Administration, SRES = Special Report on Emissions Scenarios, SEA START = Southeast Asia Global Change System for Analysis, Research & Training Centre

Analysis Group (CSAG) at the University of Cape Town.[6]

For the purpose of validation, GCM model outputs were compared with observed historical data that is available for Can Tho City (~20km from the project site). The historical data available covered the time period 1978–2004 (26 years) and the simulated baselines had similar ranges of 20 to 40 years. The observed and modelled baselines were compared,

[6] CSAG data was obtained from the "WeAdapt" joint project between CSAG and the Stockholm Environment Institute, available at www.weadapt.org.

resulting in the selection of the Geophysical Fluid Dynamics Laboratory GCM (gfdl_cm2_0) developed by the U.S. National Oceanic and Atmospheric Administration as the most appropriate model platform for the study (Figure 7). Most other models performed well with the exception of (i) csiro_mk3_5, which significantly underestimated wet season average temperatures, and (ii) echam4_PRECIS, which did not accurately replicate the historical data and simulated historical temperatures on average between 1.3°C–4.7°C higher than the observed data.

A similar assessment was undertaken for precipitation, for which the GCM gfdl_cm2_0 also performed well, confirming suitability for the study.

The historic average annual ambient air temperature is 26.7°C at Can Tho (Table 3). The data indicate that there is little monthly or seasonal variation in average daily temperatures, with a slight seasonal reduction in the order of 1 to 2 degrees during the wet season when cloud cover inhibits solar radiation, and a peak in temperature at the end of the dry season. On a daily time-step, temperatures can vary by 6 to 7 degrees on average during a day, peaking in the mid-30s and dropping to the low 20s overnight.

For plant operations, the variability in daily temperatures together with the longer-term monthly averages define the design air temperature. The O Mon IV project is designed for an ambient air

Figure 7a. Comparison of Baseline with General Circulation Model Projections in the Mekong Delta: Average Monthly Temperature

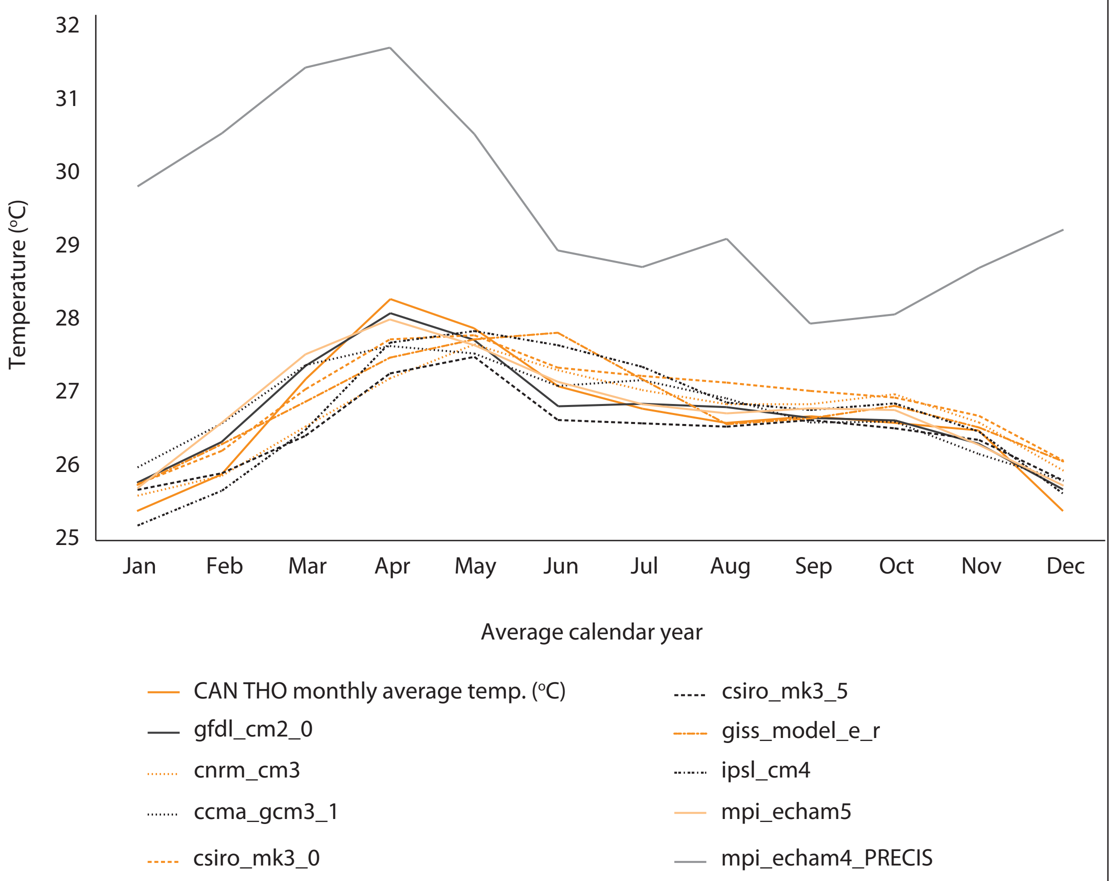


Figure 7b. Comparison of Baseline with General Circulation Model Projections in the Mekong Delta: Total Monthly Precipitation

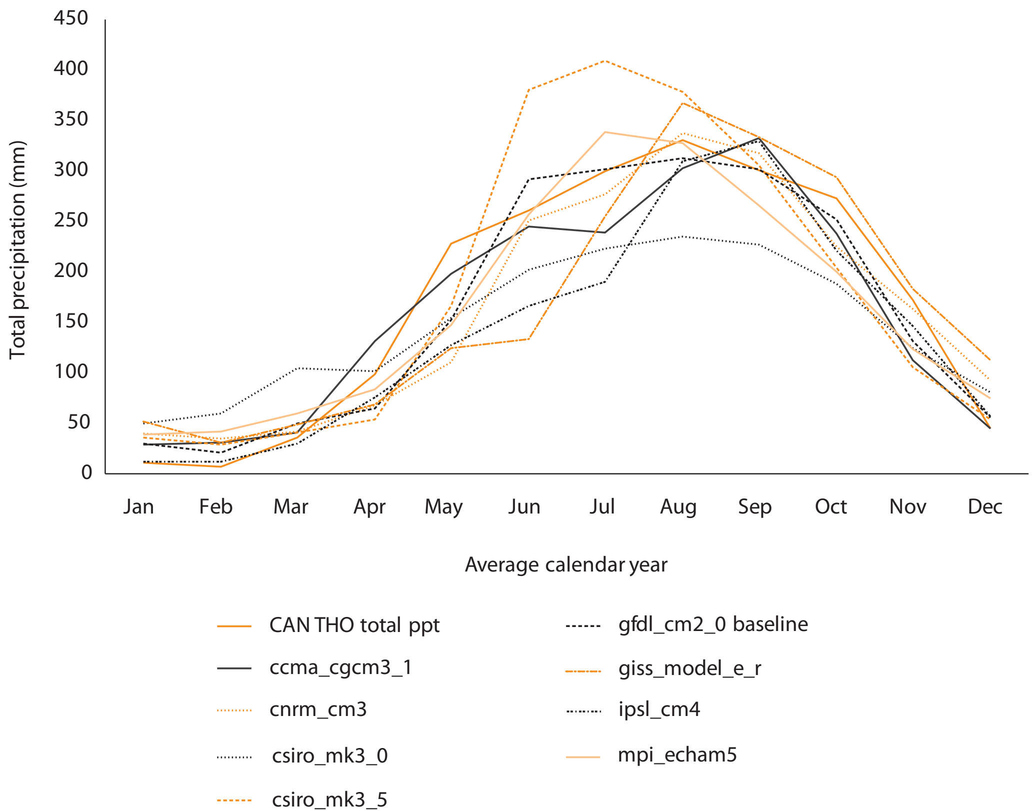


Table 3. Can Tho Average Monthly Temperatures (1978–2004) (°C)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
mean	25.4	25.9	27.2	28.3	27.9	27.1	26.8	26.6	26.7	26.6	26.5	25.4	26.7
max	33.5	34.7	36.0	36.6	36.7	35.2	34.5	34.2	34.1	33.6	33.5	33.0	34.6
min	17.8	18.4	17.7	21.8	22.0	21.4	21.4	21.1	22.2	21.2	19.3	17.0	20.1

Source: Power Engineering and Consulting Company No. 3. 2009. *Technical Design Document: O Mon IV 750MW Combined Cycle Gas Turbine*. Ho Chi Minh City, Viet Nam.

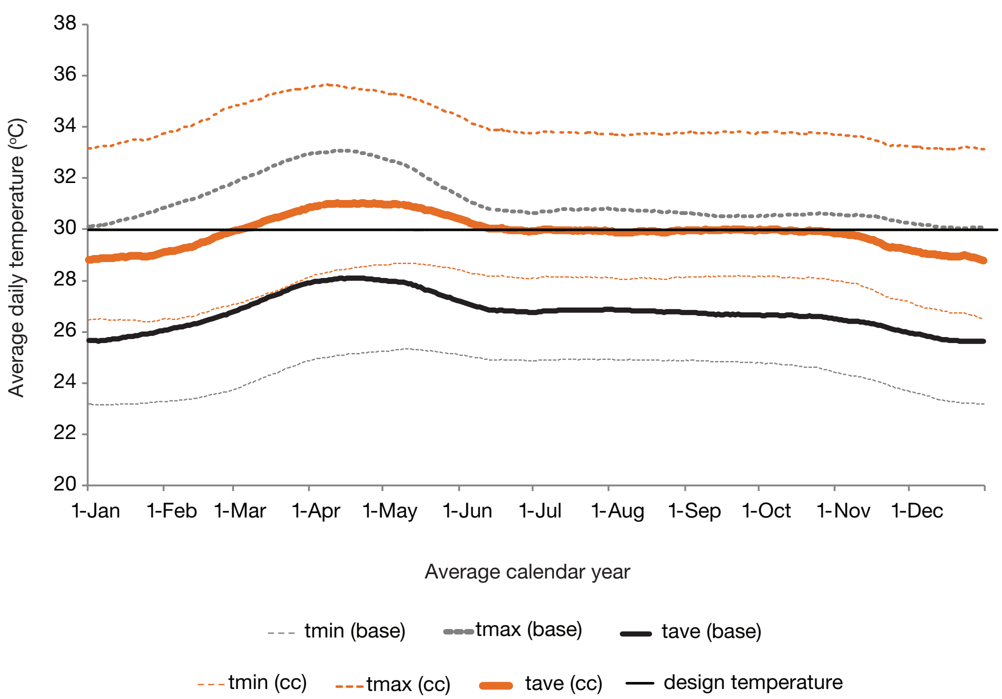
temperature of 30°C. This design temperature is on average 3.3°C above the long-term historical monthly average. However, the intra-daily variability in temperatures means that the design temperature is regularly exceeded for short periods of the day. The selection of the design temperature reflects an optimization of plant productivity and operational and capital costs based on historical conditions. A higher design temperature would require greater capital costs as components would need to be redesigned, while a lower design temperature would adversely impact plant production.

To explore the climate change impacts on the plant, the selected GCM outputs were analyzed for minimum, maximum, and average daily temperature. The daily time-step was chosen so that detailed temperature distribution profiles could be developed for typical years under baseline and climate change conditions. These were used to predict how power production, plant efficiency, and fuel consumption would change. In so doing, it is important to acknowledge that variability in daily values of variables projected by GCMs are not considered to be accurate.

With climate change, it is projected that average daily ambient temperature over the period 2045–2065 will increase by 2.8°C to 3.4ºC in the Mekong Delta (Figure 8). The average daily temperature will rise to 29.9°C, while the variability in daily temperature will be slightly reduced. Figure 8 shows the computed average temperature (tave) with climate change (tave cc) and without (tave base) change in comparison to the O Mon IV design temperature of 30°C. As made clear in the figure 8, while average temperature always remains below the design temperature without climate change, it is projected that average temperature will exceed the plant design temperature at the end of the dry season in the climate change scenario.

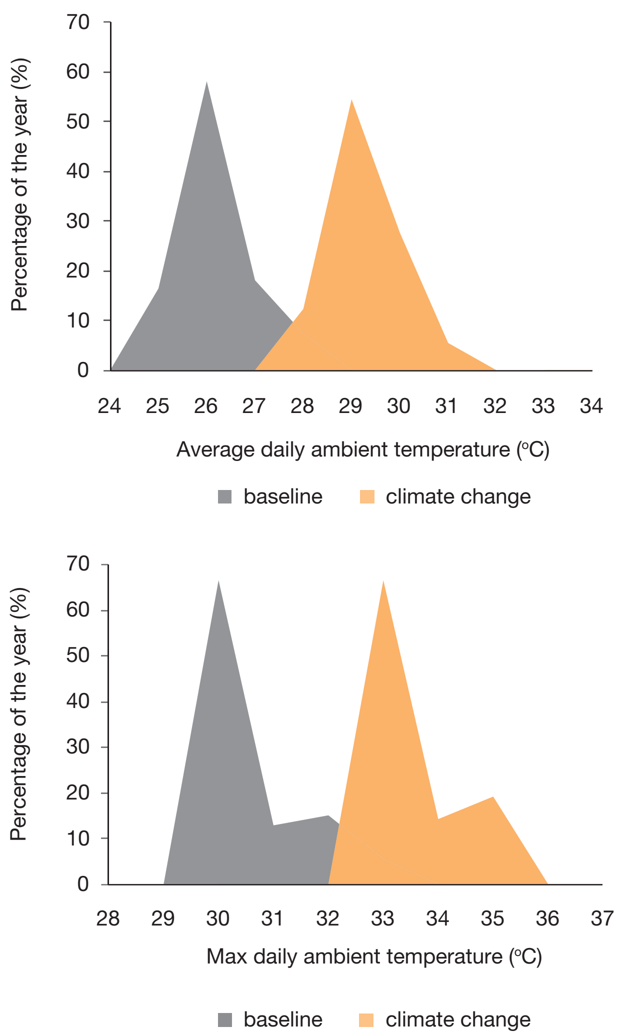
Changes will also occur in maximum daily temperatures. Under typical historic conditions, mean maximum daily temperatures are below the plant design temperature 66% of the year. By the end of the plant economic design life, the maximum daily

Figure 8. Computed Change in Average Ambient Temperature Bands with and without Climate Change (2045–2065)



tave: average temperature

Figure 9. Frequency Distribution Curves of Daily Temperatures under Baseline and A2 Climate Change Scenarios



temperature will exceed 30°C year-round, reaching temperatures of up to 35.6°C (Figure 9). It is estimated that with climate change, average daily temperatures could be greater than the plant design temperature for approximately 5.5% of the year.

If actual temperatures were to be as projected, plant performance would be reduced.

2. Assessing the Potential Impacts of Increased Air Temperature

O Mon IV has a 2-2-1 configuration consisting of two gas turbines, two heat recovery steam generators, and one steam turbine. The first electricity production phase in the plant consists of two air-cooled gas turbines, which utilize air as a working fluid and are therefore vulnerable to changes in ambient air temperature. Typically for combined cycle gas turbine plants, power output and energy efficiency decrease as air temperature increases. This is because an increase in air temperature reduces air density and the mass flow of air intake to the compressor, and creates a similar reduction in heat transfer efficiency of the air cooling system.

These losses result in reduced gas turbine power output and a reduction in the pressure ratio within the turbine, with a subsequent reduction in energy efficiency. To compensate for this, plants can restore the mass flow by increasing the flow rate through the compressors. However, this increases power consumption of the compressor. Variation in other climate factors (pressure, humidity) can also affect performance but to a significantly smaller degree and have not been identified as direct threats.

In a CCGT plant, gas turbines contribute approximately two-thirds of the power production, while the steam turbine contributes the remaining third. The CCGT power output curve is dominated by the gas turbine output curve, and it is expected that changes in air temperature will have more significant impact on plant power output than changes in water temperature.

For temperatures greater than 15°C, the net efficiency of a CCGT is comparable with the steam process. While the net efficiency of the steam process is not significantly impacted by rising temperature, the net efficiency of the CCGT process increases with rising air temperature until approximately 30°C, and then decreases as ambient temperature continues to rise. The O Mon IV plant is currently designed for peak efficiency at 29°C–30°C, which will decline with additional temperature increases.

By quantifying the change in ambient air temperature, predictions can be made on the loss in efficiency, power output, and change in fuel consumption over the plant's design life.

In order to understand how the O Mon IV plant may respond to changing air temperature, the study team, together with PECC3, performed simulations of plant power output and efficiency with increasing air temperature. The simulations used the design and machinery specifications as given in the technical design document for O Mon IV (PECC3 2009) and varied the design temperature by increments of 0.5°C between 25°C and 36°C.

According to the literature,[7] with each one-degree temperature increase above 30°C, power output of the gas turbines drops by 0.50%–1.02% while efficiency drops by approximately 0.24%. Steam turbine power output and efficiency are not significantly changed by changing air temperature, while net CCGT power output drops by 0.3%–0.6% and net efficiency drops by approximately 0.01% per degree above 30°C.

Consistent with findings available in existing literature, the net plant efficiency under the PECC3 simulations peaked at 29°C, and then exhibited a gradual linear decrease in efficiency with further increases in temperature (Figure 10). This relationship can be approximated as linear for temperatures greater than 29°C, with a 0.01% decrease in efficiency with each 1°C increase in temperature.

Power output of O Mon IV showed a strong and decreasing linear trend ($R^2 = 0.999$) according to the equation

$$P(T) = -24.54\ T + 4465.6$$

where P(T) is energy output measure in GWh per year. Based on this trend, there is an approximate 0.57% decrease in power output for each degree increase in air temperature (Figure 11).[8]

Figures 10 and 11 serve as a guide for climate change impact and present the trends in power output and efficiency based on changing average temperatures with the assumption that other parameters of the statistical temperature distribution remain unchanged. Using the results of the PECC3 simulations for efficiency and the changes to the ambient temperature distribution curve, it is then possible to estimate the changes in power output and fuel consumption over a typical year and over the design life, assuming an average 6,000 operating hours per year.

First, the energy output (E, measured in GWh) can be calculated by integrating power output over the temperature range observed in the temperature distribution curve

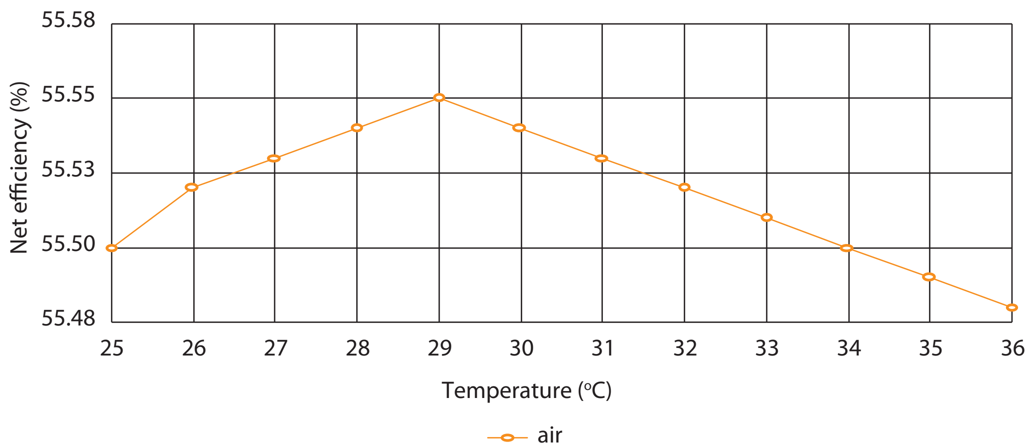
$$E_{Tm} = \sum_{T=28}^{T=37} f(T) * P(T) * 6,000$$

where T_m is the average temperature,
P(T) is the power output at temperature T (GW),
f(T) is temperature distribution curve for temperature T, and 6,000 is the average number of hours of full power per year.

7 See Kelhofer et al. 2009 and Drbal et al. 1996.

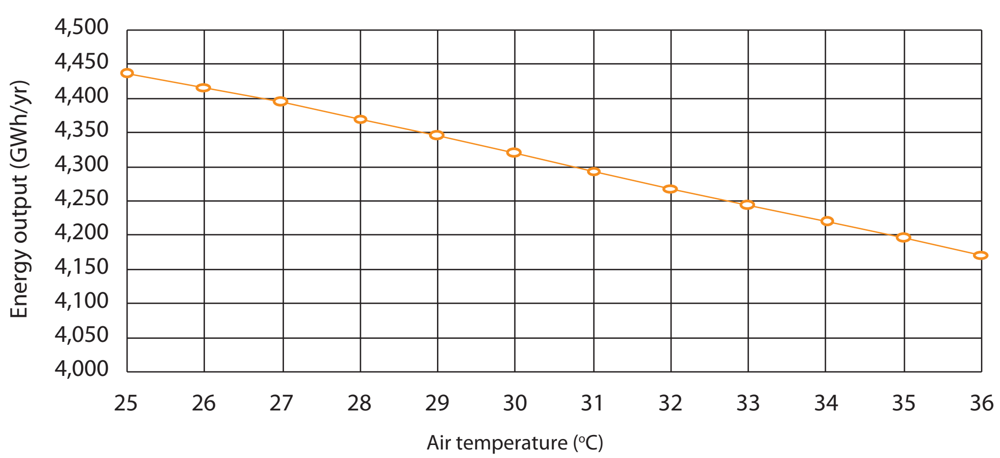
8 It may appear peculiar that power output (Figure 11) decreases over the entire range of temperature while net efficiency increases up to 29ºC (Figure 10). With a gas turbine, power output and energy efficiency decrease as air temperature increases. On the other hand, with a steam turbine, air temperature increase leads to a rise in exhaust gas temperature, which in turn improves the power output and efficiency of the steam turbine. The CCGT O Mon IV power plant has a configuration of 2-2-1: two gas turbines each with a power output of 260–290 MW, two heat recovery steam generators with a capacity of 714 tons/h, and one steam turbine with a power output of 264–289 MW. A decrease in the output of the gas turbines would have cause greater impact to the system than the increase in the output of the steam turbine. Since gas turbines represents two-thirds of the overall power output from O Mon IV, overall output decreases with temperature increase.

Figure 10. Change in Plant Net Efficiency with Air Temperature



Source: Power Engineering and Consulting Company No. 3. 2010. *Detailed O Mon IV Plant Simulations for Changes in River and Air Temperatures*. Ho Chi Minh City, Viet Nam.

Figure 11. Change in Plant Power Output with Air Temperature



Source: Power Engineering and Consulting Company No. 3. 2010. *Detailed O Mon IV Plant Simulations for Changes in River and Air Temperatures.* Ho Chi Minh City, Viet Nam.

Based on this analysis, it is estimated that power output in 2040 could decrease by 74.0 GWh due to changes in air temperature alone, or a 1.7% reduction in annual power output compared to the baseline scenario without climate change.

B. Changes in Water Temperature

1. Quantifying Future Water Temperature

The direct impact of climate change to the intake water temperature for the once-through cooling system is to increase water temperature through greater heat exchange between a warming atmosphere and the river system.

As the ambient air temperature increases, more heat will be transferred to the water column, increasing the temperature of the river water. The cumulative impacts of natural heating and discharge of cooling water will exacerbate increases in river water temperature, particularly during the dry season when water levels and sediment concentrations are lower and flow velocities are slower, allowing for greater penetration of light into the water column. Based on the projected changes in air temperature, simulations were made to quantify the change in average, maximum, and minimum water temperature, both at the surface and at the plant's water intake. Simulations were undertaken for two representative water years under baseline and climate change conditions: (i) 1997, an average hydrological year; and (ii) 2000, a hydrologically extreme year. In addition, a Cyclone Linda magnitude storm episode was simulated for a shorter period for both years in order to analyze an extreme storm surge situation.[9] The impacts of storm surge and more intense flooding under climate change are to marginally increase water levels and hence reduce the areas with elevated water temperatures during these events. It should be noted that the temperature variation is expected to be higher because of varying wind conditions and ambient water temperature. In this study constant average values have been used.

The main impacts of climate change on the river water temperature include

- 3–6% increase in the range of intake water temperatures during average years (Table 4);
- 5–10% decrease in the range and variability of intake water temperatures during extreme/wet years;

Table 4. Impact of Climate Change on Average Daily Temperature Ranges at the O Mon IV Intake

	Average Daily Temperature Range		% of Year ≤ 29.2°C	
	Baseline (°C)	Climate Change (°C)	Baseline	Climate Change
Average year	30.5 (28.0–34.8)	33.9 (31.5–38.7)	46.5%	~0%
Extreme wet year	30.3 (28.0–34)	33.8 (32.0–38.2)	51.5%	~0%
Average year storm surge episode	29.8 (29.0–30.9)	33.4 (32.8–34.7)	69.8%	~0%
Extreme wet year storm surge episode	29.7 (29.0–31.0)	33.5 (32.8–34.8)	67.2%	~0%

[9] Cyclone Linda struck the Ca Mau peninsula in 1997 and represents one of the most significant storm events to hit the delta in recent history. Sufficient hydrometrological data is available from this event to replicate the storm event in the modeling, simulating a "direct hit" on the Hau River mouth.

- increase in the average intake temperature of 3.5°C–4.0°C (Figure 12), with a higher projected temperature increase in the dry season, which can have significant consequences for plant efficiency and reliability; and
- significant decrease in the proportion of the year when river water temperature is at or below the design temperature of 29.2°C. Under historic average and extreme flood years, the water temperature at the O Mon IV intake will be equal to or below the design temperature for 46%–70% of the year. With climate change influences, the average river water temperature will rarely be below the design temperature of 29.2°C (Figure 13).

2. Assessing the Potential Impacts of Increased Water Temperature

While air temperature is the critical link between the plant topping cycle and the surrounding environment, it is river water temperature that connects the bottoming cycle. Exhaust heat from the topping cycle is used to produce steam in the HRSGs, which is then used to drive a steam turbine. After passing through the turbine chamber, the steam needs to be cooled back to a liquid so that it can be transported back to the HRSGs and reheated.

The once-through cooling system employed at O Mon IV draws in untreated water from the Hau River and uses the temperature differential between the cooling water and the working fluid (steam) to condense the steam and return it to the HRSGs. The cooling system has a determining influence on the efficiency of the steam process, which can be described by the theoretical Carnot efficiency, η:

$$\eta = 1 - \frac{T_C}{T_H}$$

where

T_C is the absolute temperature of the cold source (river water) and

T_H is the absolute temperature of the hot source (coolant).

The greater the difference between river water and coolant temperatures, the greater the efficiency of heat transfer. Since the temperature of the coolant is not projected to change, reductions in efficiency will occur through increases in the river water intake temperature.

In order to assess the specific impacts these projected changes in river water temperature may have on the plant, detailed simulations were undertaken for O Mon IV using the technical specifications in the technical design document (PECC3 2009). These simulations varied the temperature of river water at the intake structure to assess the impacts on cooling efficiency. Figure 14 shows the relative efficiency as a function of river water temperature. For river water temperatures greater than 25°C, there is an approximately parabolic relationship between water temperature and efficiency, expressed by the following equation:

$$\varepsilon = -0.006\, T_{river}^2 + 0.2988\, T_{river} + 51.96$$

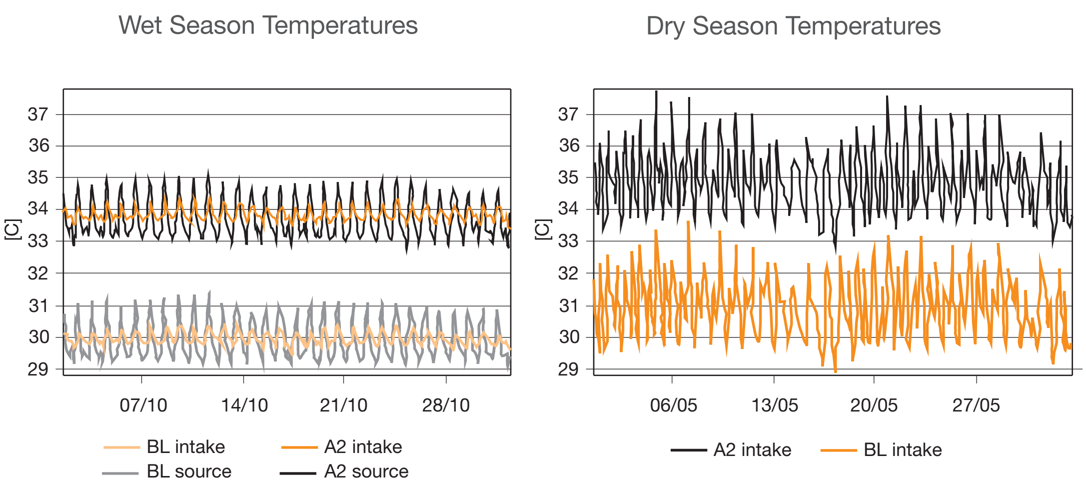
where T_{river} is the river water temperature in degrees Celsius.

Increasing river water temperature and the resulting efficiency reduction could also have an adverse effect on energy output. Based on this analysis, annual power output in 2040 could be reduced by 25.3 GWh due to changes in river water temperature alone, representing a 0.6% reduction in power output. Net efficiency could also decrease by 0.3%, down to 55.2%.

C. Synergistic and Cumulative Vulnerability

The performance impacts reported in previous sections quantify the expected annual impact at the

Figure 12. O Mon IV Intake Water Temperatures (°C)



Wet season temperatures: light grey = baseline surface temperature, light orange = baseline intake level temperature, black = surface temperature with climate change, orange= water intake temperature with climate change.
Dry season: orange = water temperature at intake under baseline conditions, black = water temperature at intake with climate change.

Figure 13. Frequency Distribution Curves of Average Daily River Water Temperatures under Baseline and A2 Climate Change Scenarios

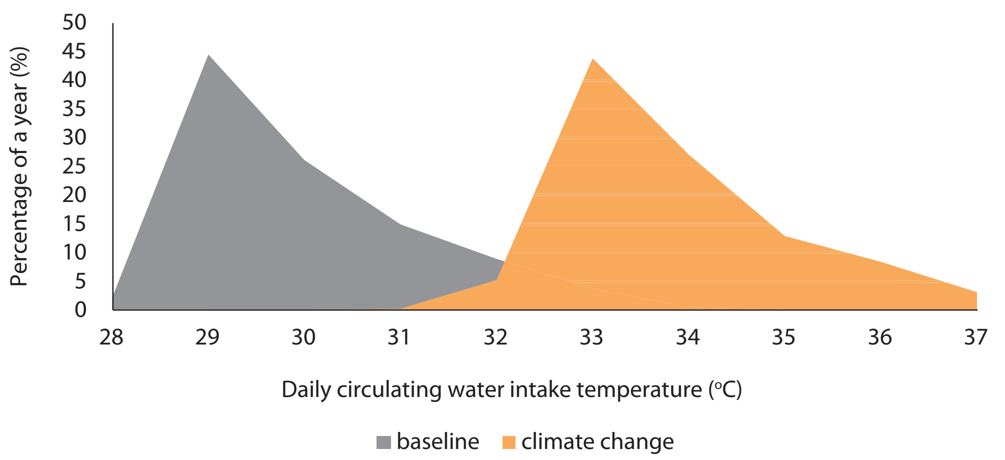
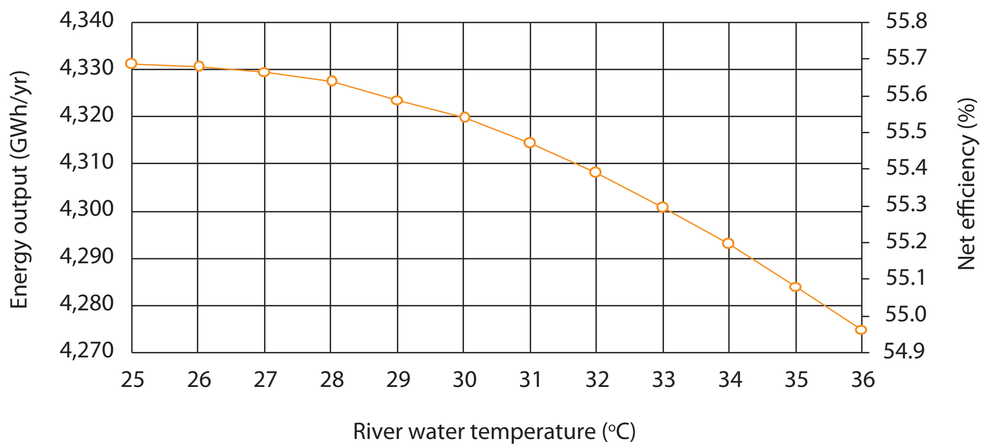


Figure 14. Relative Efficiency and Energy Output of O Mon IV as a Function of River Water Temperature



Source: Power Engineering and Consulting Company No. 3. 2010. *Detailed O Mon IV Plant Simulations for Changes in River and Air Temperatures.* Ho Chi Minh City, Viet Nam.

year 2040 for changes in individual parameters. This section synthesizes the total impact for all parameters combined and assesses the cumulative and combined impact across the design economic life of the plant. While the former is a relatively simple exercise, the latter requires further understanding of shorter-term climate change trends between now and 2040.

Quantifying short-term trends in climate through the use of GCMs is difficult. For this study, the cumulative impact of climate change on performance is made under the following assumptions:

- The rate of change in impact is expected to start slowly and increase over time.
- Consequently, the project start date represents operations with no climate change impact, while the year 2040 represents the maximum impact expected over the economic design life.
- The rate of increase in climate change impact is expected to be nonlinear.

Based on these assumptions, the cumulative impact can be considered as the integral of a climate change polynomial trend function over the design life. A linear trend was not considered representative of the rates of change in climate and impacted systems. A linear trend also provides a higher estimate of the cumulative losses over the design life, so the nonlinear polynomial function was selected to present a more conservative estimate of the impact. The combined and cumulative impacts on plant power output and energy consumption were assessed using this methodology. As part of the synergistic trends, a sensitivity analysis was also undertaken of the flooding impact to development of hydropower in the Mekong Basin.

1. Plant Efficiency

Given the projections presented earlier, the O Mon IV plant could experience a 0.32% reduction in net efficiency in response to increasing river water temperature, with a marginal 0.02% increase in efficiency due to increasing air temperature up to 29°C. The results indicate that changes in efficiency are dominated by the steam cycle, with a 0.3% drop in net efficiency expected during the plant's economic life (Figure 15).

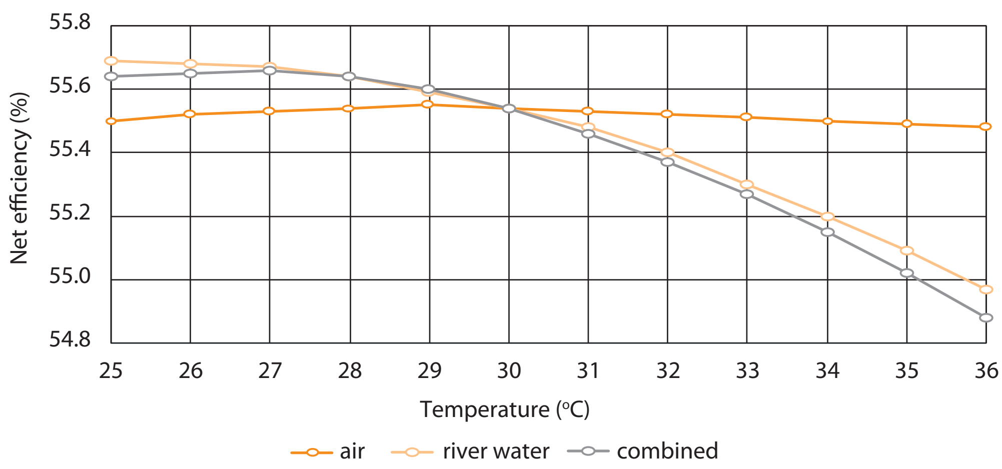
2. Power Production

The O Mon IV gas turbines contribute approximately 66% of the electricity output of the plant; similarly, the losses in overall power output are dominated by the impact of climate change on the topping cycle (Figure 16). Changes in ambient air temperature can have a significant effect on the performance of the topping cycle, reducing annual power output by 74 GWh or 1.7% of the total. Increasing river water temperature could also reduce annual power output by 25.3 GWh under climate change—providing a total combined annual reduction of power output in the order of 99.3 GWh or 2.5% of annual plant production by 2040.

The combined impacts of climate change on power output over the life cycle of the plant are presented in Table 5. Total power output could be reduced by approximately 827.5 GWh over the 25-year economic design life, with effects more severe in later phases of project operations. Over the design life of the plant this represents a loss in power output of 0.8 %.

At a nominal electricity purchase price of 6.78 cents/kilowatt hour, the combined loss in power output would amount to a reduction in 2040 revenue in the order of $6.73 million. Using a 10% discount rate, the present value of cumulative lost revenues over the period 2015–2040 amounts to $9.36 million. If power loss were to follow a linear trend between 2015 and the estimated end value in 2040, then the present value of lost revenues reaches $18.79 million.

Figure 15. Change of Efficiency of O Mon IV against Air and River Water Temperatures

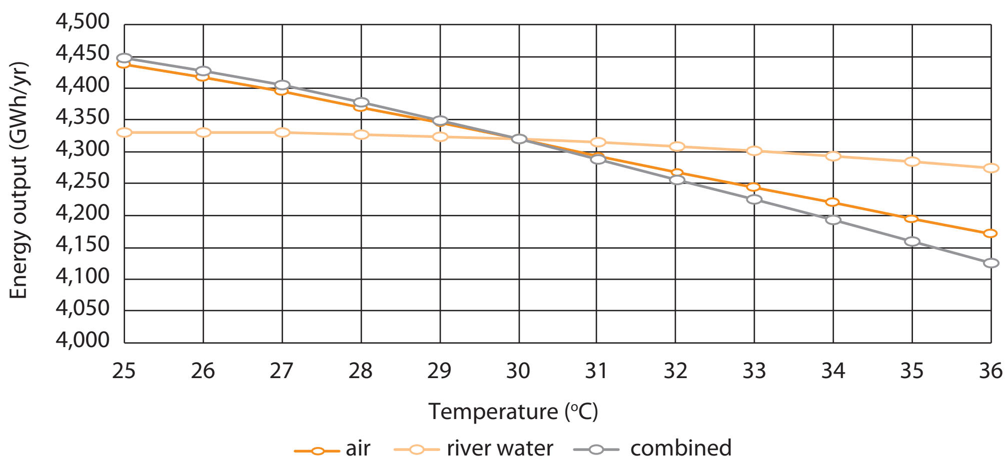


Source: Power Engineering and Consulting Company No. 3. 2010. *Detailed O Mon IV Plant Simulations for Changes in River and Air Temperatures,* Ho Chi Minh City, Viet Nam.

Table 5. Combined and Cumulative Impacts of Climate Change on Power Output (gigawatt-hours)

Climate change vulnerability	Resulting from increasing air temperature	Resulting from increasing water temperature	Combined annual loss of power output	Cumulative loss over 2015–2040	Loss of total power output over plant life
Estimated loss in power output	74.0	25.3	99.3	827.5	0.8 %

Figure 16. Change of Energy Output of O Mon IV against Air and River Water Temperature



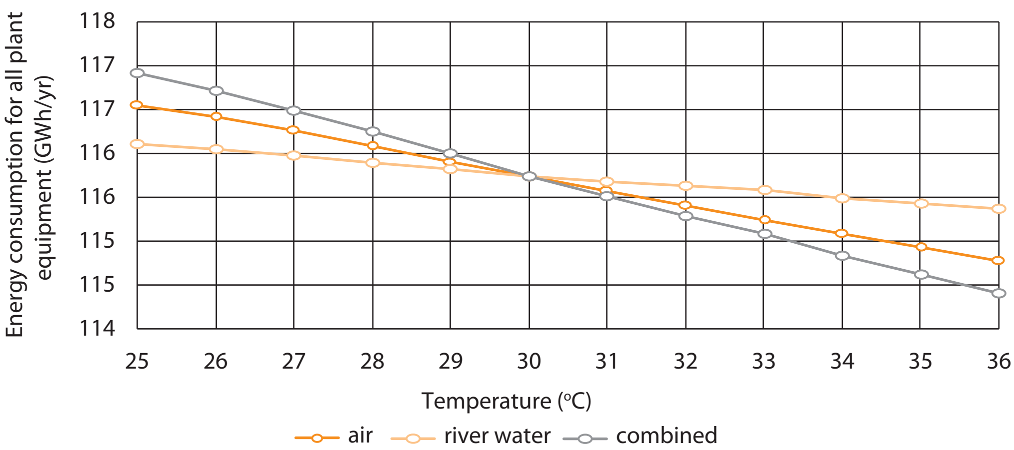
Source: Power Engineering and Consulting Company No. 3. 2010. *Detailed O Mon IV Plant Simulations for Changes in River and Air Temperatures.* Ho Chi Minh City, Viet Nam.

3. Fuel Consumption

Reductions in electricity production will result in a slight reduction in fuel consumption (Figure 17). By 2040, electricity consumption by the O Mon IV plant itself is expected to decrease by 0.77 GWh due to air and river water temperature increases (0.52 GWh from air temperature increase and 0.24 GWh from water temperature increase).

This represents a benefit for plant performance from climate change, but it is of substantially smaller magnitude than the reduction in the output of the plant over the same period. The performance simulations used in this study have taken this minor improvement into account in the quantification of the overall impact.

Figure 17. Change in Fuel Consumption of O Mon IV against Air and River Water Temperature



Source: Power Engineering and Consulting Company No. 3. 2010. *Detailed O Mon IV Plant Simulations for Changes in River and Air Temperatures*. Ho Chi Minh City, Viet Nam.

The analysis shows that there is a slight increase of 0.02% in net efficiency due to air temperature increase and there is a decrease of 0.3% in net efficiency due to river water temperature increase. These result in a relative increase of fuel cost of $1.07 million in 2040. In present value terms, the total loss over the 25 years of the plant's economic lifetime is estimated to reach $1.5 million (using a 10% discount rate).

4. Aggregate Loss

In aggregate, and given the numerous assumptions made in the analysis, it is estimated that the present value of the costs of climate change to the O Mon IV project could reach approximately $10.8 million.

This estimated loss could be interpreted as follows: All other things being equal, the project owner may be willing to invest up to $10.8 million (in present value terms) to avoid these estimated losses.

These estimates, which were derived within the context of Viet Nam's official emissions scenario, remain relatively small. It should not be presumed that analysis of other power plants in the country or region would yield identical results. Climate change impact and vulnerability assessments for energy infrastructure should be undertaken at the project level.

Setting Priorities for Adaptation

A. Ranking Climate Change Impacts

The total impact of climate change on the O Mon IV power plant is estimated at $10.8 million over the economic design life of the plant in present value terms. Given the estimated total costs and revenues of the project, this estimated loss, in the case of the O Mon IV power plant, remains relatively small. Nonetheless, given the overall demonstrative purpose of this assessment, the analysis proceeds with an assessment of adaptation options. For this purpose, the study team utilized an assessment matrix framework to characterize and rank the direct threats facing O Mon as well as the key strategic vulnerabilities of the plans.

The methodology is simplified from the rapid impact assessment matrix and scores the impact for each *threat-sensitivity* coupling as presented in Table 6 (Pastakia 1995). Scores for individual couplings range from –3 (major disbenefit) to +3 (major benefit).

These are then tallied to give totals for each threat and for each sensitive plant component. This methodology allows for a weighted indicator of priority for each threat and for each plant component.

Results are presented in Table 7. The most significant threats projected include rising air and river water temperatures. The impact of climate change is one of reduced performance and compromised processes,

Table 6. Ranking Scales for Identifying Key Areas of Vulnerability

Magnitude of Threat	Magnitude of Cumulative Threat	
+3 = major positive benefit	> +6	= major positive impact
+2 = significant improvement in status quo	> +4	= significant positive impact
+1 = improvement in status quo	> +2	= improvement in the status quo
0 = no change/status quo	– 1 to +1	= no change/status quo
–1 = negative change to status quo	< –2	= negative change to the status quo
–2 = significant negative disbenefit or change	< –4	= significant negative disbenefit
–3 = major disbenefit or change	< –6	= major negative disbenefit

not damage or loss of assets. The components most vulnerable to reduced performance are the gas and steam turbines and the air compressors. The cooling water pumps are also significantly vulnerable to climate change. Most other components are expected to have minor vulnerability to climate change in comparison.

B. Preliminary Scoping of Adaptation Options

This section provides a scoping of potential technological and management solutions, providing comments on their suitability for O Mon IV.

Table 7. Rapid Climate Change Vulnerability Summary Matrix

CLIMATE CHANGE THREAT	No. Units	Air Temp. (°C)	River Water Temp. (°C)	Coolant Discharge Feedback (°C)	Flood Water Levels (m)	Flood Volumes (m)	Climate Change Threat Score
PLANT COMPONENT							
I. Gas turbine							
Compressor (X2)	2	–3	0	0	0	0	–6
Gas turbines (x2)	2	–3	0	0	0	0	–6
Generators (x2)	2	0	0	0	0	0	0
Step-up transformers (x2)	2	0	0	0	0	0	0
Controlling equipment	1	0	0	0	0	0	0
II. Steam turbine							
Heat recovery steam generators (x2)	2	1	0	0	0	0	2
Steam turbine (x1)	2	0	–2	–2	0	0	–6
Generator (x1)	1	0	0	0	0	0	0
Condensate pump (x1)	1	0	–1	–1	0	0	–2
Controlling equipment	1	0	0	0	0	0	0
III. Coolant cycle							
Intake structure	1	0	0	0	0	0	0
Pumping system	2	0	–1	–2	0	0	–6
IV. Storm water management							
Culverts & drains (conveyance)	1	0	0	0	0	–1	–1
Discharge outlets	2	0	0	0	0	–1	–2
V. Closed cooling water system							
Inlet structure	1	0	0	–1	1	0	0
Discharge channel	1	0	0	0	0	0	0
VI. Oil storage tank	1	0	0	0	0	–1	–1
VII. 500 kV switchyard	1	0	0	0	0	–1	–1
		–5	–5	–6	1	–4	

1. Rising Air Temperature

Gas Turbine and Compressors

The biggest impacts may be experienced in the topping cycle, making it the highest priority for adaptation. However, the adaptation for the topping cycle requires a commitment early in the design process.

There are several options for adaptation that revolve around pretreatment of the intake air or redesigning the topping cycle technology to accommodate a changed environment:

- **Customize turbine technology:** The fabrication of gas turbines is typically customizable to each project, as manufacturers are able to alter generic products to better suit design specifications. An effective adaptation response may be to redesign the gas turbines to accommodate the expected effects of climate change.
  Technically, this is likely to be the most suitable adaptation option to maintain productivity of the gas turbine system, though it may be difficult to implement given the level of project development. If the redesign of the gas turbines is not an option, alternative options include the following:
- **Install inlet air cooling:** This option attempts to reverse the climate change trend of increasing air temperature by adding a cooling process before use. The two most common options for inlet cooling in gas turbine applications are evaporative coolers and refrigeration chillers.

  - Evaporative coolers are more effective for hot, low-humidity climates and would not be suitable for O Mon IV due to average year-round humidity levels of 83% reaching average monthly maximums of 99% (PECC3 2009, Loud 1991).
  - Refrigeration/chiller coolers are not constrained by ambient humidity. The operating principle is similar to the cooling water heat exchangers proposed for the steam turbine cycle. It works by directing air flow past a heat exchanger filled with colder fluid, which causes condensation in the air flow and a reduction in temperature.
- **Upgrade the compressor:** A third adaptation option is to compensate for the reduced air density by increasing the flow rate, as this can maintain the design mass flux. This can be achieved by upgrading the compressor to a larger model. Detailed engineering calculations are required to size the required compressor for this option. As with the other options, this would represent a significant investment in both capital and operational costs.

Steam Turbine

Increasing air temperature exerts a minor positive influence on the power output of the steam turbine and would not require adaptation.

2. Rising River Water Temperature

Steam Turbine

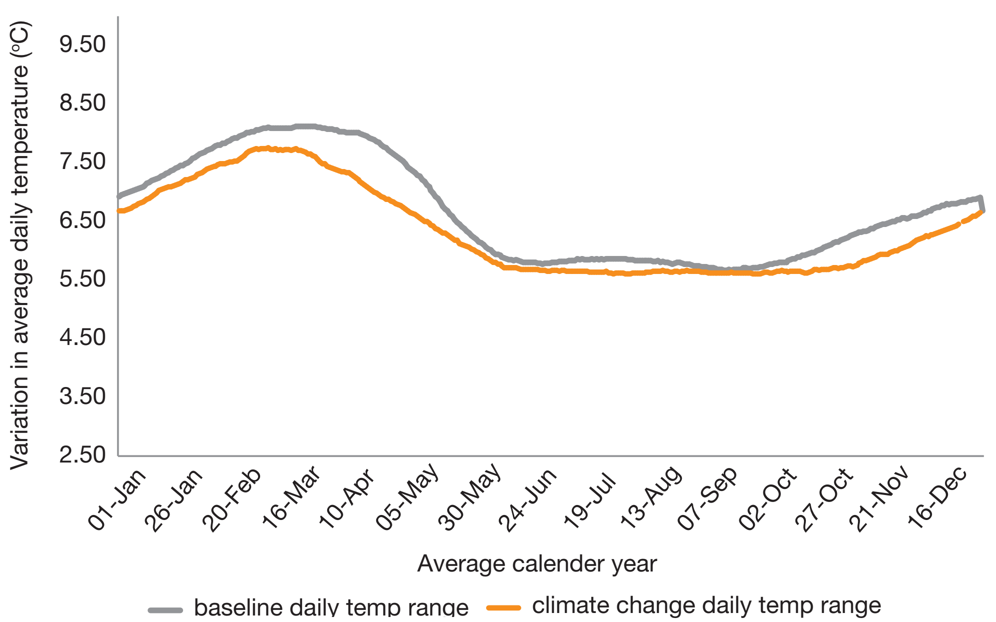
The magnitude of performance impacts on the bottoming cycle are approximately half the magnitude of impacts on the topping cycle, but the variety and relative simplicity of adaptation options prove more attractive for adaptation. Increasing river water temperature has a significant influence on the efficiency of the steam turbine and power output. A number of adaptation options are available, including the following:

- **Use a free-cooling option:** Free-cooling systems are nonrefrigerated cooling systems that rely on a nearby heat sink as a source of cooling. They operate in a similar manner to a heat exchanger in that lower nocturnal air temperatures (the heat sink) are used to reduce the temperature of a working fluid. Other heat sinks include deep sea water and high altitudes.
  The system operates by introducing an additional step in the cooling water circuit before its use.

Assessment of historic and projected daily ambient temperatures indicates that daily fluctuations in temperature are in the order of 5.5°C–8.0°C (Figure 18), with an average daily minimum temperature of 24.4°C (27.7°C with climate change). In the case of the O Mon IV power plant, this is not likely to be a suitable option as the drop in nocturnal temperatures is not likely to produce sufficient cooling potential. Another option would be to modify a chiller for this.

- **Upgrade the heat exchanger:** Increasing the size of the heat exchanger would allow greater surface area contact between condensate and coolant, improving the performance of the cooling water process.
- **Increase flow rate:** Increasing flow rate at the cooling water pumps would pass a greater mass of fluid through the exchangers, increasing heat transfer capacity. This could be done through a number of different alterations to the cooling water pumping system. Each of these pumping options would first require a pipe dynamics assessment of the cooling water system to ensure that an increased flow rate does not lead to excessive friction in the pipe network, which reduces efficiency.
- **Retain the existing pump design and open the throttle:** Flow rates in the two proposed cooling water pumps are controlled by a globe valve at their outlet. The aperture size of the valve can be used to alter the flow rate in the cooling water system. According to operational behavior in O Mon IV, these globe valves are normally kept at 70%–80% open in order to satisfy the design flow rates for the cooling water system. There is some capacity under this system to increase the flow rate by fully opening the globe valves, which may partially mitigate the loss in performance expected with climate change.

Figure 18. Average Daily Fluctuation in Air Temperature at O Mon IV



- **Add a backup pump unit:** An alternative option, offering greater flexibility while still adhering to the original design, is to add another smaller pump to the cooling water system. This pump could be designed to satisfy the incremental flow demand required to restore the design mass flow rate, and when used in conjunction with readjustments to the globe valves, may not need year-round use (use may be limited to the dry season and periods of low flow, or during high tides when coolant feedback is peaking).
- **Convert to hydrocoupling:** The cooling water pumps planned for O Mon IV are fixed-speed drive pumps designed for optimal performance at a single speed. These pump units have been used widely in southern Viet Nam because the relatively constant year-round temperatures do not require intensive monitoring and adjusting of flow rates, so the pump can be sized against the design flow rate with confidence that there will be limited variance under day-to-day operations. In northern Viet Nam there is significant seasonal and even monthly variation in temperatures, which has resulted in a preference for hydrocoupling or variable-speed drive pumping systems. These pump stations are much more flexible than the fixed-drive units and allow the operator to optimize pump efficiency over a range of working flow rates.
- **Revise management of coolant discharge:** Coolant feedback at the water intakes exacerbates the impact of increased river water temperature induced by climate change. Performance of the bottoming cycle could be improved by reducing the proportion of coolant waters entering at the water intake.
- **Redesign the intake:** The current design places the intake close to the river bank and conveys the water into an underground pit through a 30-meter-wide screened opening. Approximately 40%–50% of the water at the bank is coolant blowback, dropping to 20% 100–120 m out from the bank. By moving the intake structure further into the center of the river channel, it may be possible to reduce the percentage of coolant waters entering the intake by as much 40%–50%, which will reduce the temperature of the intake waters.
- **Redesign the discharge structure:** The current open channels discharging coolant waters from the O Mon complex enter the Hau River approximately 750 m downstream of the O Mon I plant and immediately adjacent to Vam Co Creek. Effective adaptation options for coolant management at discharge include those that (i) increase coolant temperature drop in the conveyance channel prior to intercepting the Hau River, (ii) increase mixing of coolant into the Hau River water column, or (iii) increase the distance between the discharge outlet and the intakes.
- **Improve the discharge channel:** Downstream of the discharge channel, the river channel widens considerably. Discharging further downstream or further into the center of the river channel could improve mixing of coolant waters and avoid the concentration of coolant waters along the adjacent bank downstream at the O Mon complex. In practice this would be difficult to achieve, may interfere with other river uses, and would need a scoping study to assess options.
- **Increase retention time in the discharge channel:** A longer retention time in the coolant discharge system could allow for greater reduction in coolant water temperatures before entering the Hau River system. This would require significant space, as increased retention time would result in a longer discharge channel or the inclusion of a retention facility with a large surface area.

3. Phasing in Adaptation Responses

Entry points for adaptation arise at different stages of the project time line. Ideally, adaptation planning should be initiated at the feasibility/design phase of a project because this allows for the greatest capacity for integration. However, adaptation entry points also exist at later stages in the project, including the construction and operations phases.

The following potential adaptation entry points have been identified in the context of power plant projects:

- **Investment planning phase:** Before procurement begins, there remains an opportunity to modify design elements to help restore plant performance in a warming climate. This would suit all adaptation options listed earlier. It would be critical to consider adaptation options that require redesign of civil works at this stage, as they will typically have longer design lives and so fewer entry points further along the time line.
  Also critical to this entry point is the preparation of a detailed adaptation plan. This could be undertaken separately or as an integrated plan for the entire power complex.
- **Gas turbine replacement:** The gas turbines are one of the major plant components and are also flagged as the components most vulnerable to climate change. The replacement of the turbines midway through the plant design life offers an opportunity for customization or redesign to suit the ambient temperature profile in a warming climate.
- **Major equipment replacement:** Typically, major plant equipment is replaced once every 7–10 years. These dates offer suitable entry points for bottoming cycle adaptation, especially those relating to the cooling water pumping system or heat exchangers.
- **Refurbishment and lifetime extension:** The end of the design economic life offers the opportunity for major redesign of the plant, and many components will need replacement.

Comprehensive adaptation responses for O Mon IV could be phased to synchronize with these entry points. For example, adaptation to increasing river water temperatures could be phased using the above entry points. This would allow sufficient time for studies required for optimal selection of adaptation options. In terms of impact, it would be acceptable to defer response to the first major replacement of cooling water pumps, as the incremental rise in river water temperature over the next 10–12 years will be smaller than in the following 15–18 years of operation. Hence, while many adaptation options may be best incorporated at the initial investment phase, in some instances there may be value in postponing the implementation of adaptation options as these can be designed to address observed changes in climate variables as opposed to projected changes. This may reduce the potential for misallocation of scarce resources. A detailed adaptation schedule would form one of the major outputs from comprehensive adaptation planning.

Conclusions and Recommendations

In a warming climate, the current system design is projected to experience losses in efficiency and production and increases in fuel consumption which, over the design life, represent economic losses of $10.8 million in present value terms. In other words, society should be willing to invest up to approximately $10.8 million in present value terms to offset these projected losses. Through an overall rapid estimate of potential costs, and the scoping of adaptation options, it is likely that some climate change impacts can be mitigated through the appropriate phasing of adaptation responses.

Project development for O Mon IV has proceeded to the investment phase and aspects of the design may be difficult to change. However, there remain a number of important entry points for adaptation in the plant life cycle that must be considered. These include (i) the current planning phase, (ii) replacement of the gas turbine (~12 years), (iii) replacement of other major equipment (three times over the design project life), and (iv) end of the design economic life when refurbishment and lifetime extension are being considered.

Adaptation responses may focus on three critical impact areas that drive the loss in performance:

- **losses in power output and efficiency**, due to increases in air and river water temperature,
- **increased fuel consumption**, due to increase in river water temperature, and
- **reduced efficiency of coolant discharge system**, due to increased river water temperature.

More than 86% of the total economic impact of climate change is felt through a drop in power output of the power plant. Adaptation options are focused on the gas turbine technology and revolve around pretreatment of the intake air or redesign of the topping cycle technology to accommodate a changed environment.

The magnitude of performance impacts on the bottoming cycle are half the magnitude of the topping cycle, but the variety and relative simplicity of adaptation options prove attractive for adaptation. There are three groups of adaptation options for improved performance of the bottoming cycle: (i) reducing the intake water temperature, (ii) increasing the performance of the cooling water system pumps and heat exchangers, and (iii) improving management of the coolant discharge plume.

The analysis reveals that in order not to violate existing environmental standards in Viet Nam and to avoid adverse impacts on power generation, retrofitting additional equipment (such as a cooling tower) may be required in the future (assuming that actual temperatures fall within the range of current projections). Such retrofitting will require that space be available in proximity to the power plant for the installation of the equipment. Hence, while such investment may be postponed, it is advisable to ensure that the needed space will be available if indeed such an investment proves necessary. Adaptation approaches of this nature have been referred as "climate readiness," indicating that while climate proofing may not be recommended today, a cost-effective course of action may be to ensure that the investment (the project) is ready for adaptation in the future.

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Adaptation to Climate Change: The Case of a Combined Cycle Power Plant
Summary Report

This report aims to demonstrate how a rapid climate change impact assessment can be used to identify the possible impacts of climate change on a thermal power investment project. For this demonstration, the O MON IV Combined Cycle Power Station Project in Southern Viet Nam is used for illustrative purposes.

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