THE IMPORTANCE OF SITE ON HOUSE HEATING ENERGY MODELLING IN WELLINGTON

Integrating EnergyPlus with ENVI-met for site modelling

By

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Abstract

Site is an important factor in the building design process, where it is analysed to determine design strategies for responding the microclimate. It is also considered important in Building Energy Simulations (BES) where a weather file is used to represent the site location and its microclimate. However, many cases of BES in the design process use weather file from a nearby weather station rather than site specific microclimate. In fact, site microclimate can be affected by nearby parameters such as ground surface and vegetation, with unknown effects. In the Wellington, New Zealand context, micro-climates vary widely due to the local topography while suburban houses can be located on the side or bottom of a hill. These houses are likely to have different exposure to the sun and wind which can influence energy consumption for space heating.

Many studies about site-parameters impacts mainly focus on the vegetation and nearby buildings effect on microclimate. Only a few estimated the impact of site-parameters on building energy use and mostly their cases are in urban areas (flat terrain). Unfortunately, site parameters, such as altitude and slope, associated with the Wellington topography (hilly terrain) have never been examined. This thesis investigates the importance of site parameters on house heating energy modelling for the Wellington context. BES software, EnergyPlus, was used and explored to identify limitations in modelling site parameters. An attempt was made to solve these limitations through the integration with microclimate software. Three microclimate software programmes were reviewed: ENVI-met, UWG (Urban Weather Generator) and CFD (Computational Fluid Dynamic) software.

ENVI-met was selected to generate the local air temperature and relative humidity affected by site parameters, which was used for EnergyPlus weather-file modification. A parametric study of ENVI-met basic input with model evaluation was also conducted. The results of parametric test integrating ENVI-met with EnergyPlus showed that ENVI-met mostly produce insignificant impacts of site parameters on house heating energy, unlike the results found in the literature review. This is likely due to the cool weather conditions (winter in Wellington) used in simulation, which suggests that the idea of microclimate modelling using ENVI-met is not applicable for house heating energy modelling in the temperate, Wellington context.

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Abbreviation and Glossary

BES	**Building Energy Simulation**
BPI	Building Performance Index. The heating energy of the building divided by the product of the heating degrees total (the minimum of 12 and the degree months to a base of 14°C) and the sum of the floor area and the total wall area
CFD software	Computational Fluid Dynamics software. A software use based on mathematics and physics (Navier Stokes equations) to analyse and a gas or liquid flows
ConfigWizard	A component in ENVI-met V.4.3.2 to create and edit basic input settings
DEM	Digital Elevation Manager. A feature in ENVI-met SPACE to create ground elevation per grid area or slope model
ENVIguide	A component in ENVI-met V.4.4 to create and edit basic input settings, which replaces ConfigWizard in V.4.3.2 with a different input display
ENVI-met	A 3D-microclimate-model software designed to simulate the surface-plant-air interactions
epw	EnergyPlus Weather Format
Grid cell	The smallest 3d unit which shapes the whole 3d model in ENVI-met
idf editor	an optional component of the EnergyPlus installation for creating or editing EnergyPlus input data files (IDF)
km	Turbulent Exchange Coefficient
LAD	Leaf Area Density. Leaf surface per cubic meter (m^2/m^3)
LAI	Leaf Area Index
LBC	Lateral Boundary Condition. The way the ENVI-met model behaves at its lateral boundaries
LBC -Cyclic	The values of the downstream model border are copied to the upstream model border (Provided from V.3)
LBC -Forced	The values of the one-dimensional model or from the forcing data are copied to the border (Provided from V.4)
LBC -Open	The values of the next grid point close to the border are copied to the border for each time step (Provided from V.3)
LEONARDO	A component in ENVI-met to perform 2d and 3d analysis of output variables (Visualisation)
OpenStudio	Plugin for the SketchUp software to create and define the 3D model for EnergyPlus model
Receptor	A tool in ENVI-met model (SPACE) that can be specified in any grid cell to record the detail value of the output variable
RH	Relative Humidity

Simple Forcing tool	A tool in ENVI-met model (via ConfigWizard and ENVIguide) to input 24-hours of air temperature and relative humidity for Lateral Boundary Condition (LBC)
SPACE	A component in ENVI-met model to create 3D microclimate model
TKE	Turbulence Kinetic Energy. Turbulence equation used in ENVI-met to predict the turbulence in the air
UWG	Urban Weather Generator. A software estimates the hourly urban canopy air temperature and humidity due to Urban Heat Island (UHI) effect

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1. Introduction

1.1. Site, Design and Building Energy Simulation (BES) -The Problem

Site is an important factor in the process of planning and designing a building. From early in the design process, site analysis is central to determining how a building should respond to the local climate. From a bioclimatic-design perspective, site analysis is fundamental when choosing design strategies for heating, cooling and natural lighting (Leskovar & Premrov, 2013).

Site is also an important factor in Building Energy Simulations (BES). Building Energy Simulation (BES) software uses a weather file that represents the site location and its microclimate, from a nearby weather station, often located at airports. However, the weather-station microclimate can differ from the site-specific microclimate. Site factors such as orientation, slope, ground surface and vegetation can affect the local microclimate, and mostly, they are not considered in energy modelling. The consequences of this are an unknown in energy calculation.

This study investigates the importance of site in energy modelling. It assesses which site factors are most important in the energy simulation process and those that can largely be ignored.

1.2. Microclimate and house in Wellington, New Zealand

In the context of Wellington, micro-climates vary widely, as they are strongly influenced by the local topography (NIWA, 2014). Wellington houses can be located on the side or bottom of a valley. They are likely to have different access to sun, wind, temperature, etc., which all strongly influence the building's energy consumption, especially for space heating requirements. Therefore, heating energy use for houses in Wellington might be very different from others due to its microclimate variation.

It is reported that 34% of the total energy use of New Zealand homes is for space heating, which is the largest component of most household's consumption (Isaacs, et al., 2006). Meanwhile, overheating is not a serious problem in New Zealand homes especially in Wellington as it is generally windy and has a mild temperature (Donn & Thomas, 2010). Houses in Wellington can commonly rely on natural ventilation for cooling need in the summer.

Since house heating energy requirements in Wellington can be strongly influenced by the microclimate variation, site should not be underestimated in energy calculations. This research investigates the importance of the site in house heating energy modelling in the context of Wellington, New Zealand.

1.3. The gap: the impact of site parameters from the available research

There are number of studies examining the impact of site parameters through either empirical methods (field measurement) or simulation. Some have revealed the impact of site parameters, especially nearby vegetation and buildings, on building energy use. Pandit & Laband (2010), Simpson & McPherson (1996), Huang, et al. (1987) reported that tree shading reduces the building energy use for cooling on summer while Liu & Harris (2008) and Dewalle & Heisler (1983) estimated the tree effect as windbreaks in reducing infiltration and building heating energy. Other studies (Ichinose, et al., 2017) (Nikofaard, et al., 2011), examined the impact of direct shade from nearby building on heating and cooling effort.

Besides, many studies have used microclimate-simulation software (e.g. ENVI-met) to examine the impact of vegetation (grass and trees) and or built environment (asphalt and building form, configuration and its façade material) on the thermal outdoor condition or local microclimate. However, most of these studies did not estimate the impacts on the building energy use. For example, Morakinyo, et al. (2016) integrated microclimate software (ENVI-met) and BES software (EnergyPlus) to estimate the impact of tree shading on indoor and outdoor thermal conditions, but not on building energy use. Only two studies were found which had estimated the impact of local microclimate on building energy use by integrating microclimate and BES software. Yang, et al. (2012) combined ENVI-met and EnergyPlus to calculate the impact of thermal outdoor condition affected by vegetation and nearby buildings while Nikkho, et al. (2017) estimated the impact of urban wind sheltering by integrating CFD software (OpenFOAM) and EnergyPlus. These studies demonstrated that integration of microclimate and BES software can be a possible solution to estimate site-parameters impact on BES.

The majority of research about site-parameters impact had mainly focused on the vegetation and nearby buildings effects in the real world. Meanwhile, only few discussed about the importance site-parameters in BES -How they should be included or modelled in energy calculation. There are still some site parameters whose impacts have not been examined on building energy use, especially those which are associated to the hilly Wellington topography such as altitude, ground-surface and slope. The impact of vegetation and nearby buildings from available studies are also limited only to their shading and wind-sheltering effect. The impact of tree-transpiration (photosynthesis), and building-façade material on building energy use are still unknown, which can be investigated through the integration of microclimate and BES software.

1.4. Aim and objectives of this study

This study examines the importance of the site on house heating energy modelling. It considers whether some site factors are important or not in affecting the results for house heating energy calculations. For example, whether slope and vegetation are important site factors, which can increase building energy use in energy calculations, and as such, whether they should be included or ignored in energy modelling.

In general, there are a series of objectives to accomplish the main aim of this study:

1. Identification of important site parameters which should be considered in energy performance simulation. It was conducted by studying how the site affects microclimate and the energy performance of houses through a literature review in section 2.
2. Evaluation of BES software, EnergyPlus, in modelling important site parameters. Some site scenarios were established to test whether EnergyPlus can produce the results suggested as summarised in the literature review (section 2), in particular consideration of how site parameters impact on house heating energy use. The limitation of EnergyPlus in modelling site parameters is also discussed. This is addressed in section 3.
3. Development of site modelling through the integration of EnergyPlus with microclimate software. EnergyPlus is limited to only modelling some site parameters and aspects of the microclimate, which could be solved by using microclimate software in the energy modelling process. The selection of microclimate software tools and the workflow of the modelling site are addressed in section 4.
4. Review of microclimate software selected (ENVI-met). Capabilities and limitation of ENVI-met software were reviewed. It investigates the potential outputs from ENVI-met that can be used for energy modelling, which was examined in section 5.
5. Section 0 shows a method to explore ENVI-met software for site modelling in Energy modelling.
6. Establishment of standard setting and configuration for ENVI-met basic input parameters. It was done through a parametric study of ENVI-met basic input and model evaluation (validation and calibration), which were examined in section 7. The results of this were implemented for further simulation in investigating the impact of site parameters on house heating energy modelling by integrating ENVI-met and EnergyPlus. It can be useful information for designers or urban planners to produce a reliable model in an efficient way when they use ENVI-met for microclimate modelling

7. Test of integration simulation of ENVI-met and EnergyPlus in modelling important site parameters. Some site scenarios were established to test whether site parameters that cannot be modelled in EnergyPlus have a significant impact on house heating energy modelling. This is addressed in section 0.

These objectives were accomplished in order to answer the main question in this thesis:

"How important is site in house heating energy modelling?"

Answering this question explores the site-parameters impacts which can be measured through parametric testing using EnergyPlus and ENVI-met. The results of this can determine what site parameters should be considered or ignored in the microclimate modelling for energy modelling. Besides, this research also helps address the question: **How useful is the free version of ENVI-met for house heating energy modelling in Wellington context and**, **whether the idea of microclimate modelling using ENVI-met is worthwhile for energy simulation?**

2. The importance of site in energy performance of house

This section explores the importance of site on energy performance of house through a review of published literature. It aims to understand how the microclimate affects the building's energy use in relation to site parameters associated to suburban houses in Wellington (New Zealand).

2.1. Climatic level on Site

The most accurate data of microclimate condition can be produced by establishing a weather station on the site. However, this is uncommon because it requires much effort and takes a long time to record full seasonal data (Donn & Thomas, 2010). Therefore, it is more common to gather information the broader climate and observe the site characteristics which are specific to the site such as topography and landscape features (Level, n.d.).

Leskovar & Pemprov (2013) divided climatic conditions of the site into three levels: macroclimate, mesoclimate and microclimate: In general, macroclimate is the typical climatic condition in the large area of one region. This condition is influenced by the latitude (distance from the equator), altitude (elevation from the sea) and the surrounding geographic situation. The macroclimate information is based on the indicators provided by meteorological stations such as temperature, humidity, air movement and pressure as well as solar radiation and duration.

Then, in the smaller area of the region, the general macroclimate condition changes due to the physical features surrounding the local area of the site. This changes climate is called mesoclimate. It is influenced by local characteristics of the area such as large geometric obstruction, large-scale vegetation, water bodies and ground cover. Based on the physical features, mesoclimate can be generalised into several regions: coastal regions, flat open country, woodlands, valley, cities and mountainous areas (Goulding, et al., 1992)

The third level is the microclimate condition which is the specific area nearby and in the site environment. The landscape features and built environment strongly determine this condition. For instance, planted trees and neighbor buildings can affect the sun and wind entering the site.

2.2. Climatic elements affecting energy consumption of house

Thermal indoor condition is strongly influenced by the heat flows the building. The heat fluxes in the building are mainly from heat flow through building envelopes (Q_t), air exchange through ventilation and infiltration (Q_v), internal heat gain generated by human bodies and household appliances (Q_i) and solar heat gain caused by solar radiation (Q_s). The cooling or heating energy use is determined by the sum of all energy flows (ΔQ) which has to be supplied to or extracted from the building to reach a comfortable indoor climate (Leskovar & Premrov, 2013).

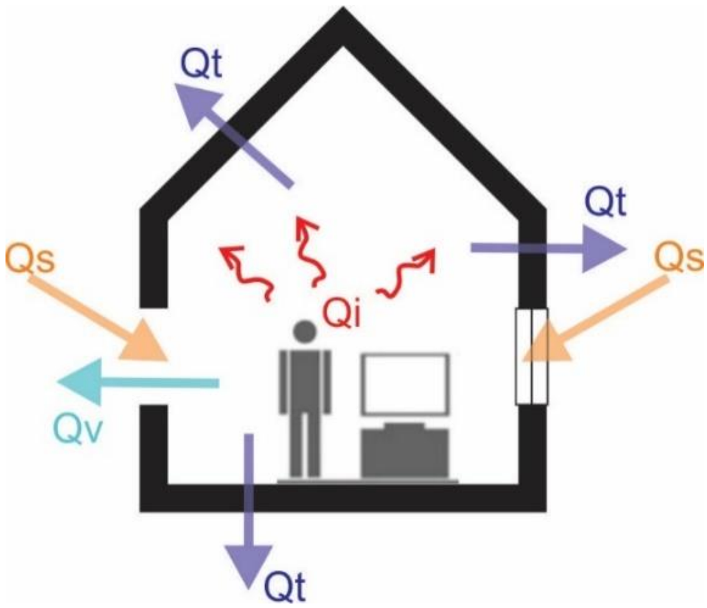


Figure 2.1. Heat flows in a building typical of cold periods (Leskovar & Premrov, 2013)

Based on that, there are four climatic elements influencing building heat gains and losses: sun, wind, air temperature, and humidity.

2.2.1. Sun

Sun influences the heat flow in building envelopes and solar heat gains through the windows in the building. In Wellington, sunlight is necessary for passive heating in the house as most of the region experiences day-time air temperature within the range of 18°-20° C in the summer while during the winter nights the average air temperature reaches 6-8°C at the coast and 3-5°C further inland (NIWA, 2014). Houses in Wellington require space heating to maintain comfort, especially during winter.

The heating energy consumption can be reduced in most homes by passive design. In this concept, solar access is utilized through glazing and thermal mass to provide warmth, while insulation maintains it by reducing heat loss. The solar availability is the most critical factor since the site which lacks or has no sunlight cannot be used for passive solar design (Level, 2016). Solar energy utilization can be beneficial for winter heating, and thus, it is essential for energy-conserving site design (Sadoun, 1992).

2.2.2. Wind

Wind control can save energy for space heating by reducing air infiltration and heat convection (Sadoun, 1992). Wind causes heat losses through air leakage and by increasing the conduction heat loss on building's surfaces, especially through windows (Donn & Thomas, 2010). Wind control can be implemented by using external windbreaks such as trees or fences, reducing both air infiltration and heat convection. Another way is to ensure the home well sealed and insulated.

2.2.3. Air temperature

The temperature difference between indoor and outdoor influences heat transfer through building envelope, as well as through ventilation or infiltration. According to the World Health Organisation (WHO) indoor temperature in the house should be kept at least 18^{o}c to provide comfort for the occupants (World Health Organization, 1987). One of the passive ways to keep indoor temperature is by installing thermal insulation in building envelopes.

2.2.4. Humidity

Outdoor relative humidity (RH) affects thermal comfort and space heating through infiltration. Humid air takes more energy to heat than dry air because it contains more water vapour with more heat capacity. RH is also associated with how occupants perceive the air temperature and it is one factor that influences much space heating requirements (BRANZ, 2017). High RH can make people feel hotter than the actual temperature while if the RH is low, people can feel cooler. For example, a 30% increase in RH leads sedentary people to feel warmer by 1^{o}C in their bodies (Berglund, 1998).

2.3.Site parameters affecting microclimate and energy consumption of house

The climatic elements affecting heat flow in the building become an essential consideration in identifying important site parameters affecting house energy consumption in the Wellington context. There are four site parameters considered important:

2.3.1. Altitude

Altitude influences ambient temperature on the site. Every 300m of increase in elevation means an average 2-3^{o}C drop in temperature (Dorward, 1990) and thus, houses which are in the higher ground require higher heating effort as it has a lower ambient temperature. In the case of Wellington, during winter nights, the western and eastern coastal strip is warmer than further inland because air temperature decreases with height above sea level by about 0.6°C for each 100m increase in elevation (NIWA, 2014).

Altitude also affects wind movement surrounding site. "Drag at the ground always causes the wind speed to be reduced, while aloft the winds are stronger" (Wallace & Hobbs, 2006). In the Wellington region, the strong gust is usually in the high country or hilly area. For example, the anemograph on Mt Kaukau (425 m) recorded monthly high average wind speed of 44 km/h whereas at Wellington Airport, the range is 25-30 km/h (NIWA, 2014).

2.3.2. Terrain

"The climate and weather of the Wellington region are characterised by strong variations in space and time, strongly influenced by the presence of Cook Strait and the rugged local topography" (NIWA, 2014). Concerning the microclimate, a large slope or hill can obstruct the site sun. For example in the context of southern hemisphere New Zealand, a house located on a south (non-equator) facing slope will get less winter sun. This can be a disadvantage as the house can not optimally utilize the sun during winter for passive heating.

Slope direction and inclination can result in warmer temperature due to seasonal effects. Conversely, in the northern hemisphere United States, a south (equator) slope with 20% gradient, receives 30% more solar radiation and will be three weeks ahead in the arrival of spring (Olgyay, 1963). Types of ground surface can also increase the local temperature, as material such as asphalt or pavement absorbs more solar radiation than grass.

Local topography also can change the wind speed surrounding the site. The wind speed can increase due to wind passing between the hills and decrease when it moves over rougher terrain. Wind speed can accelerate over open and flat areas while it is slowed down by a large area of trees and buildings (BRANZ, 2018). "A house located on top of a ridge can have heat losses 50% greater than if it were on the flat" (Donn & Thomas, 2010).

2.3.3. Vegetation

Plants and trees which are located nearby on the site can provide shade and wind barrier to the house (BRANZ, 2017). The size, porosity, number and location of the trees influence the sun and wind that reach the building. In terms of sun, nearby vegetation can be a drawback for the house as it can block the sun that is necessary during winter. The result of the empirical study (Pandit

& Laband, 2010) in Auburn, Alabama revealed tree shade was associated with increased winter energy consumption.

On mesoclimate scale, a large area of vegetation can reduce the surrounding temperature by creating shade that reduces the ground temperature surrounding the site. It can intercept 60% to 90% of the solar radiation and cause a significant reduction of the surface temperature of the ground below in the day time (Goulding, et al., 1992). Vegetation also can produce cooler and moist air in microclimate due to evapotranspiration effect– "the combination of transpiration, the release of water through stomata in plant leaves, and the evaporation of water from the ground surface" (Berner, et al., 2005).

Vegetation can become windbreaks or shelterbelts that slow down the wind speed on the site. Thus, it can reduce the infiltration as well as heat losses in the house. Dewalle & Heisler (1983) found that a 61-meter-long single row of white pine trees reduced air infiltration by 54% and space heating by 18% in a small mobile home.

2.3.4. Nearby Buildings

Nearby buildings contribute to site direct shade. Study in Canada reveals that close and large neighborhood houses on all three sides can increase the heating effort by about 10% due to building shade (Nikofaard, et al., 2011). Nearby buildings can also be a barrier that can reduce wind pressure. One study (Chang & Meroney, 2003) found that building arrangements significantly reduce wind pressure, especially when the width of the street canyon is smaller. It can reduce by 80% of wind pressure with B/H= 0.5, where *B* is the width of the street canyon and *H* is the building height.

Besides, the number or nearby buildings surrounding the site can give an impact on the local air temperature. The building surfaces can absorb solar radiation and re-radiate it. In this case, roof surface has the most significant impact on temperature increase as it is relatively low in albedo values (the fraction of solar radiation reflected by a surface) and high in thermal conductivities (Wolf & Lundholm, 2008).

2.4.Overall Summary

Site parameters that are important in affecting microclimate are altitude, topography, vegetation and nearby buildings. They are important since they are likely to influence climatic elements on site: sun, wind air temperature and humidity, that can significantly affect energy performance of house. Those parameters become a fundamental principle to test and examine BES software, EnergyPlus, in modelling site.

Table 2.1 summarises the impact of those parameters on house heating energy

Site Parameters	Factor	**Impact on**	
		Site microclimate	House Heating energy
Altitude	Altitude increase	Cooler temperature, higher wind speed	Increasing
	Altitude decrease	Warmer temperature, lower wind speed	Decreasing
Terrain	Slope shade	Block the sun	Decreasing
	Slope seasonal effect	Warmer temperature	Increasing
	Green surface	Cooler temperature	Increasing
	Impervious surface	Warmer temperature	Decreasing
Vegetation	Tree shade	Block the sun	Increasing
	Number of trees	Block more the sun and wind; increase evapotranspiration	Increasing
	More leave density	Block more the sun and wind; increase evapotranspiration	Increasing
Nearby buildings	Building shade	Block the sun	Increasing
	Low albedo surface	Warmer air temperature	Decreasing
	High conductance surface	Warmer air temperature	Decreasing

Table 2.1. The important site parameters and its impact

3. Site Modelling in the BES Software: EnergyPlus

This section explores and examines one well-known BES software, EnergyPlus, in taking account site factors. Many researchers and designers have used this software for energy and thermal-comfort simulation. This section discusses how the microclimate factors and site parameters (reviewed in section 2) are modelled in EnergyPlus. A preliminary test of EnergyPlus (Section 3.3) was also conducted to investigate the relative importance of site parameters.

3.1. Microclimate in EnergyPlus Calculation

According to EnergyPlus engineering references (U.S. Department of Energy, 2016) and a review from an earlier study (Yang, et al., 2012), the energy balance for a zone in EnergyPlus can be defined:

$$Q_{loads} = Q_{int} + Q_{conv,int} + Q_{inf} + E_{air}$$

Where:

Q_{loads} = Building heating/cooling loads
Q_{int} = Internal heat gains from lights, people and equipment
$Q_{conv,\ int}$ = The convective heat transfer between zone interior surfaces and zone air
Q_{inf} = The heat transfers due to infiltration with outdoor air
E_{air} = The change of energy stored in the zone air.

Meanwhile, the energy balance equation for building exterior surfaces can be written as:

$$Q_{sol} + Q_{lw} + Q_{conv} - Q_{cond} = 0$$

Where:

Q_{tsol} = Transmitted solar radiation
Q_{sol} = Absorbed direct and diffused solar radiation
Q_{lw} = Net longwave radiation flux
Q_{conv} = Convective heat flux exchanged with outside air
Q_{cond} = Conduction heat flux into the wall

Based on those two equations, it can be concluded that local microclimate affects energy calculation in EnergyPlus through several factors:

1. Solar radiation reaching building surfaces, which are affected by external objects surrounding the building.
2. Convective heat flux at the exterior surface, which is determined by Exterior Convection Coefficient ($H_{c,ext}$) and the difference of the surface temperature and the outside air temperature. $H_{c,ext}$ is determined by surface roughness and local surface wind speed.
3. Longwave radiation flux, which is determined by surface absorptivity, surface temperature, sky and ground temperatures, and sky and ground view factors. EnergyPlus

can use a simple assumption where the surface temperatures of ground and obstructions are the same as the outdoor temperature.

4. Infiltration, which is strongly influenced by local wind speed, air temperature and humidity

Table 3.1 shows the relationship between factors that determine EnergyPlus energy use with the important climatic elements of microclimate as well as site parameters.

Factors in EnergyPlus	**Influenced by**	
	Climatic elements	**Site Parameter**
Solar Radiation	Sun	Terrain, Vegetation and Nearby Buildings
Convective Heat Flux	Wind and Air Temperature	Altitude, Terrain (Obstruction), Vegetation and Nearby Buildings
Long Wave Radiation Flux	Air temperature	Altitude, terrain (Surface materials and its angle), vegetation and nearby Buildings
Infiltration	Wind, Air temperature, and Humidity	Altitude, Terrain (Obstruction), Vegetation, Nearby Buildings

Table 3.1. Factors in EnergyPlus associated with microclimate and site parameters

3.2.Site parameters definition

Three levels of climatic condition on the site: macroclimate, mesoclimate and microclimate become the basic principle in modelling parameters that affect site microclimate. Microclimate condition on the site is a result of the macroclimate values that are changed by mesoclimate and microclimate parameters.

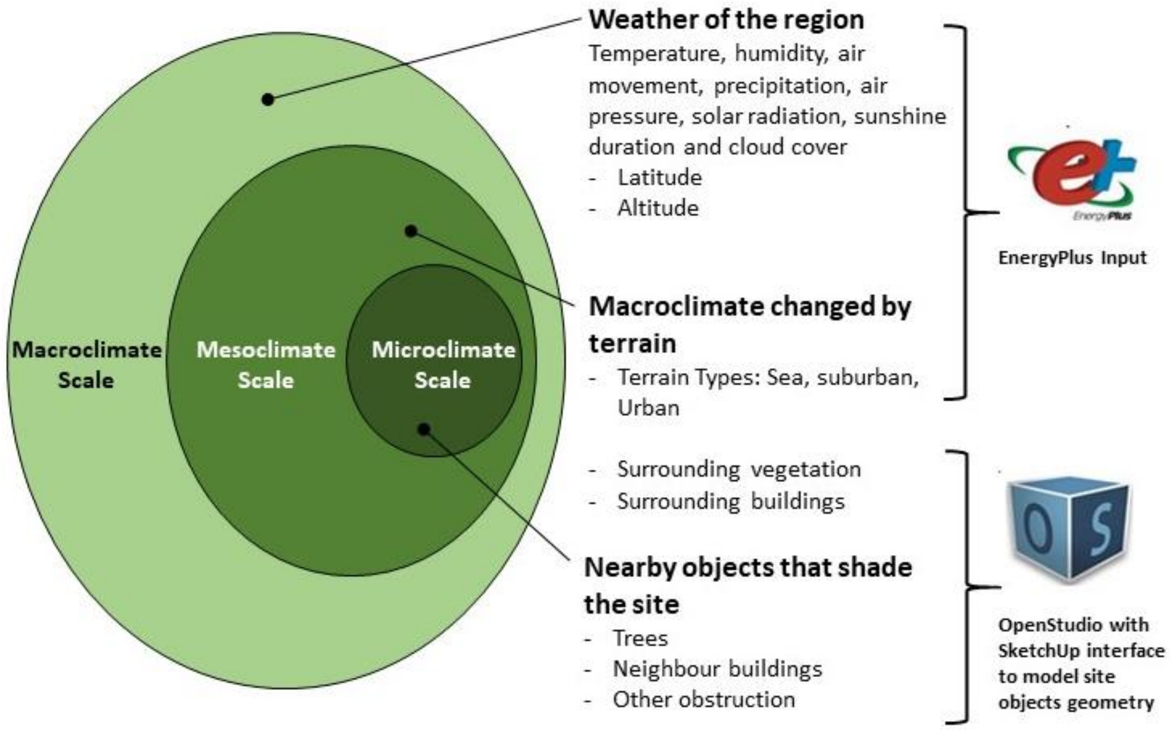


Figure 3.1. Climatic level and site parameters in EnergyPlus

The preliminary test examined EnergyPlus interfaced to OpenStudio. Energyplus provides input parameters that represent macroclimate, mesoclimate and microclimate condition. OpenStudio can model the objects that affect microclimate condition such as trees, high fences, nearby hills, and neighbor buildings through the interface of SketchUp engine and transfer them to EnergyPlus input parameters.

3.2.1. Macroclimate condition

Macroclimate condition is represented in the EnergyPlus as the weather data which should be input before running the simulation. The weather file for EnergyPlus is provided by its website (https://energyplus.net/weather) for major cities across the world, including Wellington.

The altitude might affect the microclimate on the site. In EnergyPlus, the zone elevation determines atmospheric variation that influences outdoor temperature and the wind speed in infiltration, ventilation and exterior convection calculation. The zone or surface centroid is used to determine elevation from the ground (U.S. Department of Energy, 2016a).

3.2.2. Mesoclimate condition

Mesoclimate condition is represented in the terrain condition which can be set in building object information in the EnergyPlus input IDF file. The site's terrain affects how the wind hits the building – as does the building height. The following table shows the types of terrain provided by EnergyPlus (U.S. Department of Energy, 2016b).

Terrain Type Value	Terrain Description
Country	Flat, Open Country
Suburbs	Rough, Wooded Country, Suburbs
City	Towns, City Outskirts, Center of Large Cities
Ocean	Ocean, Bayou Flat Country
Urban	Urban, Industrial, Forest

Table 3.2. Terrain input in EnergyPlus

3.2.3. Microclimate condition

The slope, vegetation and nearby buildings which give the shade to the site affect microclimate on the site. They can be modelled as external shading in OpenStudio. The tree model consists of four surfaces as this model can block the sun from all directions, and it is simple to make in OpenStudio.

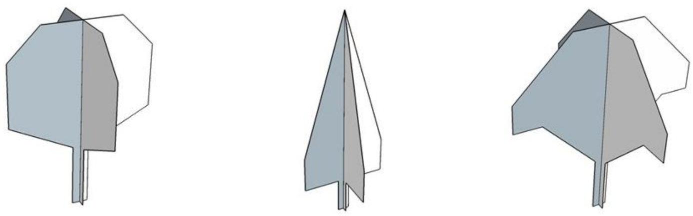


Figure 3.2. Tree geometry model in EnergyPlus interfaced with Openstudio

The tree porosity (leaves density) can be adjusted in the transmittance value of the shading surface in EnergyPlus. It will affect the shading surface to reflect the amount of sunlight passing through the vegetation. The name of a schedule of solar transmittance values from 0.0 to 1.0 for the shading surface. If a blank is entered in this field, the transmittance value defaults to 0.0, i.e., the shading surface is opaque always. This scheduling can be used to assume seasonal transmittance change, such as for deciduous trees that have a higher transmittance in winter than in summer (U.S .Department of Energy, 2016c).

3.3.The preliminary test of modelling site in EnergyPlus

The preliminary test aims to investigate whether EnergyPlus can produce results of the impact of site parameters upon energy use of house.

3.3.1. House Model Definition

The first consideration is to establish the simple design of the house model which can interact with the microclimate. The design should allow the model to get the impact of the sun and wind.

Another important consideration is that the design should be relevant to the New Zealand context. Thus, the construction: room size and window configuration of the model followed the standard and building regulation of New Zealand.

3.3.1.1. Design

The model consists of two zones. The north zone represents the living room and will be tested for the site modelling. It allows the model to interact significantly to the microclimate condition as it has three exterior surfaces: east, north, and east, that enable the room to get the impact of the sun in the three directions. The south zone represents other rooms (e.g. bedrooms, kitchen, bathrooms) whose function in the model is to provide the adiabatic surface to the living room as it is not possible that one room in the house has four external walls.

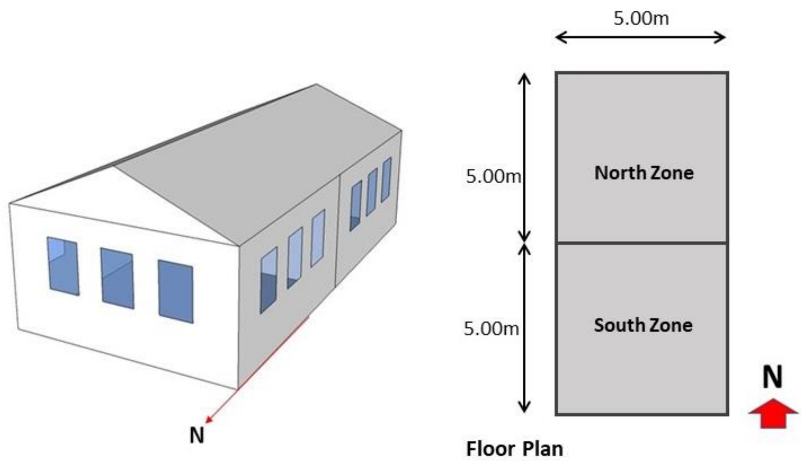


Figure 3.3. Simple house design (hypothetical model) as for preliminary test

The zone square shape was used to simplify the model, as the exterior surfaces could have the same size and window configuration. The room size followed the minimum standards of the New Zealand Building Code:

1. The model is defined as the detached dwellings as this is the simplest house category, which accommodates fewer than six people (Ministry of Business, Innovation and Employment New Zealand, 2014). As the number of occupants is identified, the minimum requirement of the room size can be determined.

2. The 25m^2-sized room accommodates five occupants, representing the habitable space of a living room and dining room (Department of Building and Housing New Zealand, 2011).
3. The habitable room should have a height from finished floor to finished ceiling of at least 2.1 m for an existing house and 2.4m in the new house (Ministry of Business, Innovation, and Employment, New Zealand, 2013). So, 2.5m ceiling height was applied in this model.
4. The total window area must not exceed a third of the total exterior wall area (Ministry of Business, Innovation & Employment, 2015). So, the entire window area applied in this model is about 20% of its wall surface as this was assumed as the moderate size. The window is 700mm wide and 1000 mm high.

3.3.1.2. Construction

The insulation value of the construction complies with NZBC Clause H1 (Based on NZS 4218:2009), for house insulation for Zone 2 as given in the following table (Ministry of Business, Innovation & Employment, 2015):

Envelope	Climate Zone for Wellington
Roof	R 2.9
Walls	R 1.9
Floor	R 1.3
Windows	R 0.26

Table 3.3. The NZBC standard of insulation value for a Wellington, New Zealand house

The construction R-Values for EnergyPlus were determined using NZS 4214:2006, which provide the information of thermal resistance (R-Value) of building components and elements (Standards New Zealand, 2006).

3.3.1.3. Considerable Input and Scenario

This section describes the input and scenario values which affect conditions inside the living-room model (The north zone). It includes occupancy, lighting, equipment, heater use, ventilation, and infiltration. The values are based on a NZ or international standard, survey or research:

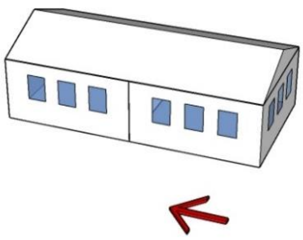
Input	Living Zone Input and Scenario Value
Occupancy	• Metabolic rate 75W per person with 60% availability from 7:00 to23:00 (BRANZ, 2007) and 0% during the night time (23:00-7:00) as occupants sleep in the bedroom. The maximum number of people in the living room is 5 people based on the habitable space for the living room (Department of Building and Housing New Zealand, 2011)
Equipment	• Internal heat was 16W/m^2 with 25% available from 7:00 to23:00 and 5% during the night (23:00-7:00) (BRANZ, 2007)

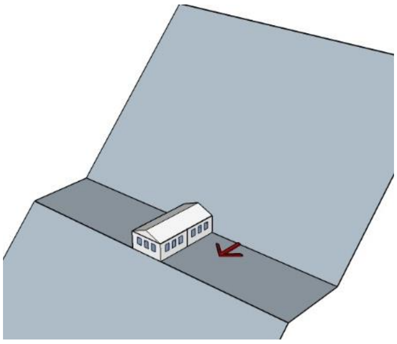
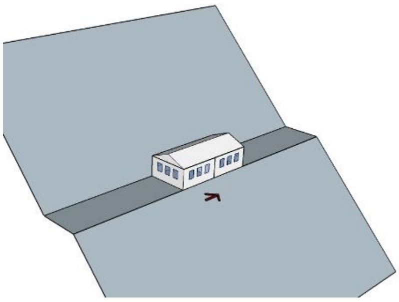
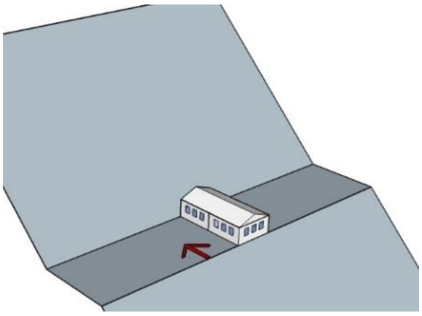
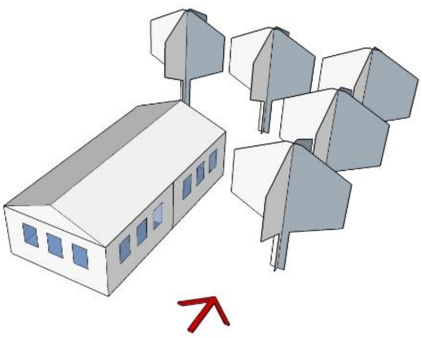
Lighting	• Internal heat was 8.5W/m² with 15% available from 7:00 to23:00 and 0% during the night (23:00-7:00) (BRANZ, 2007)
Heater use	• It was reported that the average heating season in the Wellington is from April until September (BRANZ, 2010). • The thermostat set point for heating was 18°c. This value is the minimum indoor temperature suggested by the World Health Organization (World Health Organization, 1987) • Based on monitoring during winter in 2010, almost 90 percent heat pumps were operated in the morning (07.00-09.00) as well as in the evening (17.00-23.00). Also, nearly 40% uses heat pumps during the day (09.00-17.00) while not often used overnight (23.00-07.00), which is only about 15 percent (BRANZ, 2010a). Therefore, the heater was scheduled from 07.00-23.00 in the model.
Ventilation	• The net openable area was 5% of total floor area, which is 1.25 m² in the model, based on the minimum requirement of clause G4 Ventilation-New Zealand Building Code (Ministry of Business, Innovation and Employment New Zealand, 2016). • It was assumed that the window opening is only in the morning (07.00-09.00) as the simulation period is in the winter time. • The slight opening was given in the morning during, which applied 0.125 of effectiveness of the openings. It represented the small opening of awning windows. The effectiveness is 0.25 for assumed diagonal winds (Level, n.d.), which can be assumed as the maximum opening of the awning window.
Infiltration	• New Zealand houses built after 2000 has greater airtightness which is almost 0.2 ACH (Level, 2015). This figure was used for the infiltration value in the simulation.

Table 3.4. Occupancy, Equipment, heater use and ventilation input

3.3.2. Site Scenarios

Nine site scenarios were established based on the site parameters identified from the literature review:

Scenario	Description
1. Baseline Model 	- No obstructions surrounding the site -The aim is to compare this model with other scenarios and see the differences. - Terrain type (Mesoclimate) was the suburbs in simulation input. - The elevation was 50m above sea level (assumed as the general elevation of a suburban area in the Wellington)
2. The altitude 150m	- Using the Baseline model, the elevation was changed from 50m to 150m above sea level. It was expected to have higher heating demand as higher altitudes experience cooler ambient temperature and higher wind speeds.

3. Facing-north Slope 	- Elevation and terrain were the same as the baseline model - This simulation is compared to the baseline model to see whether the slope facing north (external surface in EnergyPlus) can give the seasonal effect to the building, which leads to warmer ambient temperature. This effect was expected to result in lower heating consumption than the baseline model. - This model does not have an obstruction in the east, north and west side, which is the same as the baseline model in terms of sun exposure during winter. It supposedly has the best condition compared to the other aspects. - The extreme slope gradient was applied, which was 45^{O}, to produce a significant difference compared to the result of other slope orientations.
4. Facing-west Slope 	- This scenario blocks the east sun which has significance in heating house in the morning (the coldest time) - The result of this was compared to the facing north-slope to see whether the slope facing west has higher heat load as the model gets sun obstruction from the east.
5. Facing-south Slope 	- It was expected to have the highest heating load compared to the other aspects because the north slope obstructs the winter sun.
6. Tree shade 	- Trees were placed in the east and north side of the model because those sides block the sunlight in the morning and midday, which has significance in heating the house during winter. - The tree distance was 5m to the building, and the height was 6m. It was expected to obstruct the sun significantly and thus, has a higher heating load compared to the baseline model.
7. Tree porosity	- It aims to investigate whether the EnergyPlus can produce the difference in tree porosity.

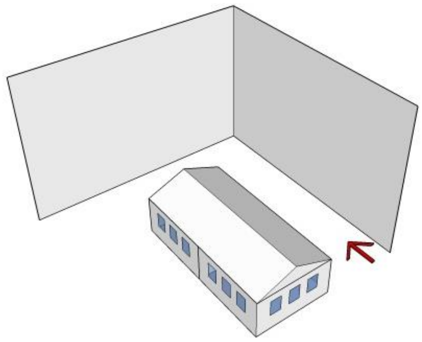
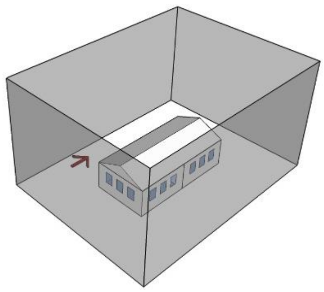
	- By using the scenario of tree shade, the transmittance value of tree surfaces (external shading) in EnergyPlus is set by 0.75 (leaf off), assuming deciduous trees. As the tree allows the more sunlight, it was expected to have lower heating consumption than the tree-shade scenario above.
8. Neighbour Building 	- The model was assumed to be obstructed by a close and larger neighbor building from the east and west side. - The height of external surfaces was 10 meters, and the offset of external surfaces was 5 meters, which are likely to give the significant obstruction to the model. - It was expected to have higher heating demand than the scenario of tree shade (6) because the area of external shadings is larger, which block more sunlight.
9. The Windbreaks 	- It aims to investigate whether the external shading surfaces can reduce the wind impact on the model and thus lessen the heat loss and increase the energy saving. - The transmittance value of external shading is set to 1.0 (totally translucent) in EnergyPlus. It led to the same condition as the baseline model regarding sun exposure as the sunlight can pass through the external surface. - The result of this scenario was compared to the baseline model. If it has less energy consumption, it means the external shading can reduce the wind factor in EnergyPlus.

Table 3.5. Site scenarios for the preliminary test

3.3.3. Quality Assurance

The BPI (Building Performance Index) calculation was done using the baseline model EnergyPlus results. It aims to evaluate whether the simulation produced reasonable results.

Ideally, the BPI value must have less than 1.55 kWh/DM m^2 to comply with the Energy Efficiency Clause H1 (Ministry of Business, Innovation and Employment, New Zealand, 2017). For evaluation, the BPI calculation of this model must not exceed too far from 1.55 or must be less than it considering that it had applied the input, according to the minimum standard of the building code.

The formula of BPI calculation is shown below:

$$BPI = \frac{Net\ heating\ energy\ use\ [kWh]}{Degree\ months\ \times (Total\ Foor\ Area\ [m^2] + External\ Wall\ Area\ [m^2] + External\ Window\ Area\ [m^2])}$$

The heating load of the EnergyPlus calculation was applied in the formula. The degree hours applied for Wellington is 22.7 (Ministry of Business, Innovation and Employment, New Zealand, 2017).

3.3.4. Results and Discussion

3.3.4.1. The BPI

The initial simulation of the baseline model was done to complete the BPI calculation. It was found that the total energy use for space heating of the north zone during the heating season (April-September) is 1935.5 kWh. Meanwhile, the whole floor and external wall area are 62.5m^2. Therefore, the BPI of this room is:

BPI = 1935.5 / (22.7 x 62.5) = 1.36 < 1.55

The BPI figure is below the maximum, meaning the model complies with the requirements of NZBC Clause H1.

3.3.4.2. Comparison and Difference

The table shows the space heating demand of the model using default Wellington weather data (Wellington WN 934360 (NIWA)), for the eight different scenarios described above, and how the results compare to those from the literature review for site impact. In general, almost all scenarios produce the results which are similar to the expectations from the literature review findings.

NO	Scenarios	Heating load (kWh)	The increase compared to Baseline (%)	Prediction based on the literature review
1	Baseline model	1935.5	-	-
2	The altitude 150m	2254.8	+16.5%	Matched
3	Facing-north slope	1938.5	<0.2%	Unmatched
4	Facing-west slope	2000.1	+3.3%	Matched
5	Facing-south slope	2095.5	+8.3%	Matched
6	Tree Shade	2019.7	+4.3%	Matched
7	Tree Porosity (Deciduous)	1979	+2.2%	Matched
8	Neighbour Building	2091.6	+8.0%	Matched
9	The windbreaks	1935.5	No change	Unmatched

Table 3.6. Heating energy use in different site scenario

3.3.4.3. Additional Testing of Site Terrain

Supplementary testing was conducted to see whether EnergyPlus can consider the wind impact on the heating demand based on the site terrain condition. Based on EnergyPlus documentation, the site terrain affects how the wind hits the building (U.S. Department of Energy, 2016b). The test used the baseline model by changing its terrain condition in the EnerpyPlus input with different states of terrain. Table 3.7 compares the heating load calculation in different types terrain condition in EnergyPlus.

Terrain Condition (using Baseline)	Heating load (kWh)	Significance (compared to the Baseline -Suburbs)
Baseline -Suburbs (Roughed, Wooded Country, Suburbs)	1935.5	-
Country (Flat, Open Country)	2345	Increase 21.1%
City (Towns, city outskirts, center of large cities)	1474.7	Decrease 23.8%
Ocean (Ocean, Bayou Flat Country)	2559.2	Increase 32.2%
Urban (Urban, Industrial, Forest)	1935.5	Same

Table 3.7. Heating load calculation in different terrain condition

The ocean and open field have a higher heating demand by nearly 30% and 20% respectively. Those locations have stronger wind exposure which leads to more heat loss and use of energy for space heating. It is likely to be realistic as such places have no high vegetation or barriers which can become the windbreaks.

Meanwhile, heating demand was decreased when the terrain condition was changed from suburbs to the city, which is also plausible as wind exposure in the city is significantly blocked by larger objects such as multi-storey buildings. There is the same value between the baseline and urban condition in EnergyPlus because those conditions have similar terrain.

3.3.4.4. Lessons: Limitations of EnergyPlus

Two scenarios do not produce the results which match the literature review. Those are: (3) the slope facing north and (9) the windbreaks.

1. North Facing-Slope

   A hill facing the winter sun experiences warmer winter temperatures than on the flat (Olgyay, 1963). However, the result of the north aspect from EnergyPlus did not indicate this as there was no reduction in heating demand. This is because EnergyPlus does not have the capability to model a ground surface that absorbs and re-radiates solar radiation or estimate the impact.

2. Windbreaks

   The external surfaces modelled in OpenStudio do not affect the wind in EnergyPlus or influence energy use for space heating. As can be seen in Table 3.6, the baseline model and windbreaks scenario have the same heating demand. Based on an experimental study (Dewalle & Heisler, 1983), external objects such as vegetation can become windbreaks which reduce wind velocity and therefore reduce air infiltration and the need for space heating.

   The impact of wind exposure on building energy use is determined by the terrain condition in the EnergyPlus "idf editor". It generalizes the wind factor based on the five terrain conditions (mesoclimate conditions): country, suburbs, city, ocean and urban.

3.4. Capabilities and limitation of EnergyPlus site modelling

Table 3.8 summarises the important site parameters that can be modelled in EnergyPlus, and how they are modelled and their energy calculation significance, is based on a documentation review and preliminary testing. The review gathered information from (1) Engineering reference and (2) Input-output reference from the EnergyPlus documentation website.

Site Model	Impact				Finding
	Sun	Wind	Ta	RH	
Altitude	-	Y	Y	-	- Different elevation of the modelled zone has a different atmospheric condition that gives a difference in energy calculation
Terrain	Y	L	N	N	- The types of terrain are generalised into five categories (LIMITED-Wind), which affect the energy calculation results - The surface of the ground cover surrounding site that can affect local temperature cannot be modelled (NO-Air Temperature) - Coverage of vegetation that can change the local air temperature and RH are not calculated (NO-Air Temperature and RH)
Vegetation	Y	N	N	N	- Vegetation can be modelled by using external shading objects. However, it only influences the sun factor but not the wind factor that hits the building in simulation (NO-Wind) - External shading objects representing vegetation does not affect the local air temperature due to outdoor shading (LIMITED-Vegetation) - Vegetation does not affect the local air temperature and RH due to evapotranspiration as there are no plants profile provided in EnergyPlus input (NO-Air Temperature and RH)
Nearby Building	Y	N	N	-	- The model and its impact are the same as modelling vegetation

Table 3.8. Capabilities and limitation of EnergyPlus in modelling site parameters (Y: Yes, L: Limited, N: No)

There are some EnergyPlus site modelling limitations, in that it:

1. cannot model physical terrain features that can impact on local outdoor air temperature and RH change. For example, the influence of ground cover, the inclination of the ground surface, number of trees, coverage of nearby buildings.
2. only calculates the impact of shade on the building model, but not that on the surrounding environment which can contribute to temperature decrease.
3. cannot consider the impact of some mesoclimate scale site parameters. For example, the trees, buildings and types of ground surfaces nearby or on the site might have a small influence in smaller scale, but, in the broader scale (meso-scale), they might impact on air temperature change and RH.
4. generalizes terrain condition which limits the wind factor. The wind factor also is not affected by the external objects. Thus, it cannot produce the specific result such as the effect of windbreaks.

3.5.Conclusion

From the review and preliminary test in modelling site issues, it is concluded that EnergyPlus can model site parameters and produce the results about the site impacts such as those found through the literature review. Overall, EnergyPlus considers site parameters affecting the sun reaching building surface, wind factor, and ambient temperature.

However, some limitations were found. Firstly, the wind factor is not affected by the external objects, and the generalization of terrain condition limits it. Thus, EnergyPlus cannot produce a specific result about the effect of windbreaks or shelterbelt. Secondly, local air temperature is only affected by the altitude. The influence of ground surface and its inclination, as well as the material of nearby building surfaces, cannot be modelled.

Site parameters which are not considered in EnergyPlus might be important in understanding real world energy performance. For example, the ground surface material surrounding the building can heat the ambient air and thus reduce winter energy heating consumption. Therefore, the consequence of EnergyPlus limitations might result in the design and construction of real buildings failing to achieve the simulated energy performance. The importance of these site parameters in EnergyPlus is the object of this research and is investigated in section 4.

4. Integration of EnergyPlus with microclimate software

The consequence of site-modeling limitations is unknown: whether site parameters that cannot be modelled in EnergyPlus are important real-world factors for house heating energy. Thus, it requires another tool that can be used to examine the importance of these parameters.

4.1. Role of Microclimate Software in Energy Calculation

Some of these limitations in modelling site parameters can be solved by using a microclimate software tool which can be combined or integrated with EnergyPlus. That software should be able to model site parameters that cannot be modelled in EnergyPlus. One practical way is to use microclimate software for generating specific local outdoor microclimate and use this output to replace or modify the EnergyPlus weather file. The microclimate software should produce:

1. Local outdoor air temperature and humidity which are altered due to physical features and the shading effect of the surrounding environment
2. Wind speed and direction which are changed due to surrounding objects such as trees or buildings.

Both local outdoor temperature and wind influence the results of EnergyPlus calculation. Based on EnergyPlus Engineering References (U.S. Department of Energy, 2016), each change the convective heat flux at the exterior surface (Q_{conv}) and the heat transfer from infiltration (Q_{inf}) which are important factors in energy balance calculation.

4.2. Criteria for the microclimate software

This section examines important site parameters that might have a significant influence on the microclimate but cannot be modelled in EnergyPlus:

- Terrain -Ground surface material and its contour (road, pavement, grass, slope). Albedo values and thermal conductivities of ground surfaces influence the local air temperature. Orientation and inclination of slope affect the amount of solar radiation absorbed by the ground surface and this can impact on the ambient temperature.
- Vegetation -Tree profiles. The number, size and type of tree contribute evapotranspiration that affects local temperature and humidity.
- Nearby Buildings -Surface material. Albedo values and thermal conductivities of building envelopes influence the local air temperature. Thus, the number and size of nearby buildings are relevant.

- Terrain (hills), vegetation and nearby buildings as shading devices. Their shading effect is not only for the building model but also for the surrounding environment. It can block solar radiation to the ground and reduce the local air temperature.
- Terrain (hills), vegetation and nearby buildings as windbreaks -They are external objects that can reduce or accelerate the wind speed.

Those site specifics will be modelled and investigated as their relative importance is unknown. Thus, it is necessary to ensure whether the microclimate software considers those items. This becomes criteria in microclimate software selection.

4.3. Possible microclimate software for the integration with EnergyPlus

A market review identified three possibly relevant microclimate software tools. This section provides an overview of them: ENVI-met, Urban Weather Generator (UWG) and CFD. This overview is based on technical software documentation on the website of each tool and previous studies using those tools to examine the site parameters that cannot be modelled in EnergyPlus, based on the criteria in section 4.2.

4.3.1. ENVI-met

"ENVI-met is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in the urban environment with a typical resolution down to 0.5m in space and 1- 5 sec in time" (ENVI_MET, 2018). In ENVI-met, the interaction between vegetation and atmosphere such as evapotranspiration and sensible heat flux for trees (due to photosynthesis) can be examined. Besides, in relation to the surfaces, the heat and mass exchange related to the soil surfaces are also considered in the simulation such as the water absorbed by the plant from the soil (Salata, et al., 2016).

An ENVI-met microclimate model is established based on grid cells, and the variables of microclimate data can be produced in each grid cell and visualised through 2D or 3D graphics. The detailed values of microclimate data including air temperature and RH can be produced via receptors that can be specified in any grid cell in the domain area.

There are numbers of studies using ENVI-met to investigate the influence of site parameters for thermal comfort study and urban design. Morakinyo, et al. (2016) examined the impact of tree shading on the outdoor while Skellhorn, et al. (2014) evaluated different scenarios of greenspace in neighbourhood level. In addition, Morakinyo & Lam (2016a) examined biological parameters of the tree such as Leaf Area Index (LAI) and Leaf Area Density (LAD) in affecting thermal comfort in the street canyon. Related to the terrain and nearby buildings, a study by Middel, et al. (2014) investigated the impact of urban form on local air temperature while, Salata, et al. (2015) measure the effects of soil and wall material on the outdoor thermal comfort.

ENVI-met can undertake Computational Fluid Dynamics analysis, and therefore, it can simulate the impact of trees or nearby buildings on wind condition. However, ENVI-met does not simulate a diurnal cycle for wind or wind direction changes (Middel, et al., 2014), which means the microclimate is based on constant wind.

The table below summarizes the site parameters definition in ENVI-met and their importance based on the technical webpage (ENVI_MET, 2018b; ENVI_MET, 2018c; ENVI_MET, 2018c) (ENVI_MET, 2017) and previous studies:

Site Parameters	How site parameters are defined (Based on the ENVI-met website	Importance (based on the previous studies)
Altitude	Not provided	-
Terrain	- Soil model: soil types and material, soil temperature and its water content - Soil elevation can be set in each grid via DEM (Digital Elevation Manager) to model the slope	- Horizontal and vertical surfaces (soil and wall) affecting outdoor thermal comfort (Salata, et al., 2016)
Vegetation	- Vegetation is treated as biological bodies interacting with the environment by evapotranspiration and photosynthesis - Profiles of plant are provided such as leaf are density, albedo, aerodynamic resistance	- Tree shade affecting outdoor air temperature (Morakinyo, et al., 2016) - Biological features: Leaf Area Density affects outdoor thermal comfort (Morakinyo & Lam, 2016a)
Nearby Building	- Nearby buildings are modelled as masses per grid, and material properties of its surface can be defined	- Building surface material affecting outdoor air temperature (Salata, et al., 2016) - Outdoor shading due to urban form (high building) has a cooling effect (Middel, et al., 2014)

Table 4.1. Definition and importance of site parameters in ENVI-met

4.3.2. UWG (Urban Weather Generator)

UWG estimates the hourly urban canopy air temperature and humidity, based on the weather file from a rural weather station (epw) as well as an input file describing the condition of the urban canyon (Massachussets Institute Technology, 2016). This software produces a morphed weather file [epw] that represents the urban microclimate which is usually warmer than the weather station due to Urban Heat Island (UHI) effect. UWG provides input parameters that describe urban morphology, geometry and surface materials.

The workflow of UWG is integrated through Rhinoceros, a CAD-based modelling software (Massachusets Institute Technology, n.d.). One study (Nakano, 2015) demonstrated using UWG as a plug-in for Rhinoceros, modelling as 3D the building masses and streets. The urban geometric characteristics were extracted using Grasshopper (an algorithmic modelling Rhinoceros plug-in). Then, using Grasshopper, the 3D geometries in Rhino are defined as different site parameters: buildings, vegetation as well as ground surfaces.

A sensitivity test and analysis using UWG was conducted by Nakano (2015) for Boston and Singapore case studies. Both cases have different climates (cold in Boston and tropical in Singapore). The test changed the value of input parameters to be ± 25% higher and lower. These high and low ranges were based on the sensitivity test conducted from earlier research by (Bueno, et al., 2013). It was found that site coverage ratio, façade-to-site ratio and sensible anthropogenic heat are the critical parameters in UWG for Boston and Singapore in affecting local air temperature and RH. Similarly, an earlier study in mild climate regions (Toulouse, France and Basel, Switzerland) (Bueno, et al., 2013) found that site coverage ratio, façade-to-site ratio, and vegetation are the most sensitive parameters.

UWG is robust enough to produce plausible results in the case of urban areas. UWG's results are comparable to a more computationally expensive mesoscale atmospheric model and much faster in simulating microclimate condition (Nakano, 2015). However, it cannot produce the results which are in the specific location on the site -it only generates a morphed weather file for the urban area. Moreover, it cannot model the wind impact surrounding the site.

Table 4.2 summarizes site parameters and importance using UWG website documentation and previous studies:

Site Parameters	How site parameters are defined (Based on the UWG documentation page)	Importance (based on the previous studies)
Altitude	Not provided	-
Terrain	- Ground surface, street, vegetation and nearby buildings geometries are modelled in 3D Rhinoceros and defined in Grasshopper	- Site coverage ratio and the façade-to-site ratio (horizontal and vertical surface) is an influential factor (Nakano, 2015) (Bueno, et al., 2013)
Vegetation	- Vegetation properties: albedo, latent fraction and tree schedule - Plant is treated as shading devices for urban canyon	- Vegetation coverage is one of the influential factors in reducing air temperature (Bueno, et al., 2013)
Nearby Building	- Construction, as well as building function, can be defined in input parameters	- Site coverage ratio and façade-to site ratio are influential factors (Nakano, 2015) (Bueno, et al., 2013), which are associated with building size - Anthropogenic heat (heat flux from building in the urban area) is an influential factor

Table 4.2. Definition and importance of site parameters in Urban Weather Generator (UWG)

4.3.3. CFD Software

CFD software can generate wind data to a specific site scenario, accounting for urban forms. This application can be utilized to calculate wind pressure coefficients surrounding the site, which can be applied to EnergyPlus.

A recent study (Cresswell-Wells, 2014) integrated CFD software and EnergyPlus to calculate urban forms effect on natural ventilation. UrbaWind was used to estimate the wind pressure coefficient (C_p). In UrbaWind, the grid system was set up to generate a Cp value for each façade, and Wind Angle of Incidence (WAI) is set every 45^o through the full compass range. Then, C_p values were entered EnergyPlus parameter input: 'AirflowNetwork: MultiZone: WindPressureCoefficientValues' object to calculate the effect of natural ventilation in the urban area.

Another approach by (Nikkho, et al., 2017) integrated CFD software with EnergyPlus. The study attempted to quantify the impact of urban wind sheltering on building energy consumption. OpenFOAM was used to produce the local wind multipliers by running eight CFD scenarios for 1 m/s wind in the eight principal directions to calculate the wind speed coefficients. Then, calculated local wind multipliers are used to adjust wind velocity in the weather data file (see Figure 4.1).

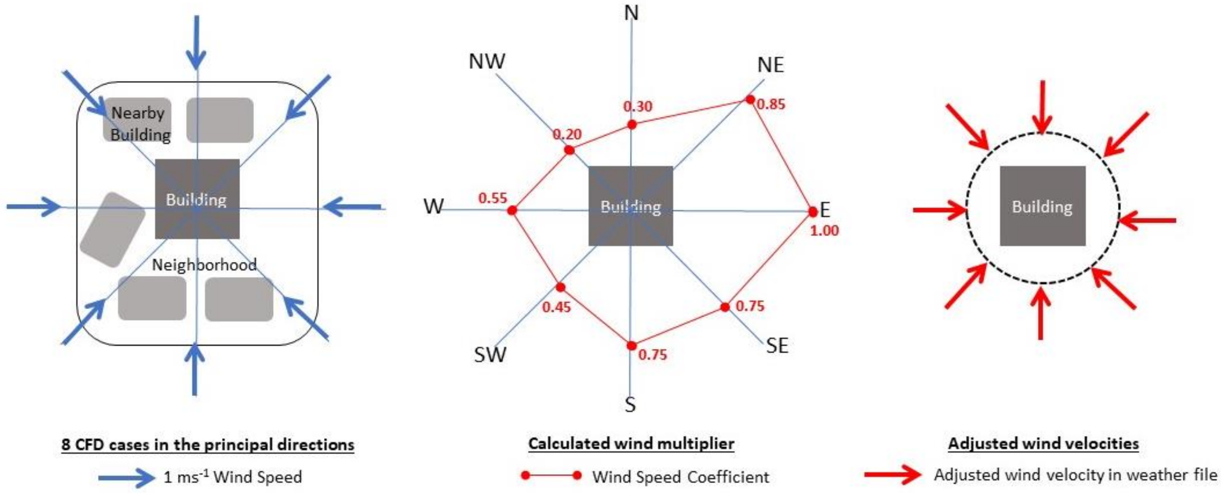


Figure 4.1. The steps performed to calculate the wind multipliers and their deployment in the weather data file (Nikkho, et al., 2017)

The framework developed by both studies revealed how to integrate CFD and BES in modelling the wind factor on a specific site. In general, both studies have similarity in using CFD, which was to produce wind coefficient surrounding the site.

The approach developed by (Cresswell-Wells, 2014) might be simpler, as the C_p values of facades produced by CFD can be entered in EnergyPlus input parameter. However, this approach only accounts for natural ventilation. Other effects influenced by wind factors such as convective heat flux at the building's surface and heat transfer from infiltration are not calculated in this approach. Meanwhile, the framework proposed by Nikkho, Heidarinejad, Jiying, & Srebric (2017) accounts for all factors (Q_{conv} & Q_{inf}) in energy calculation that is influenced by wind because the energy calculation uses adjusted weather file that contains new wind profiles based on CFD output.

4.4. Application of ENVI-met, UWG and CFD in site modelling

The table below lists the important site parameters that can be modelled in microclimate software discussed: ENVI-met, UWG and CFD, based on the established criteria (section 4.2). In general, two microclimate software reviewed (ENVI-met and UWG) fulfil the criteria since they can model almost all important site parameters that cannot be modelled in EnergyPlus. Nevertheless, they still have a limitation in modelling wind factor.

Site Parameters	Envi-MET	UWG	CFD
Terrain -Ground surface material and its contour	Y	Y	-
Vegetation -Tree profiles	Y	Y	-
Nearby buildings -Surface material	Y	Y	-
Hills, vegetation and nearby buildings as shading devices	Y	Y	-
Hills, vegetation and nearby buildings as windbreaks	L	N	L

Table 4.3. Application of ENVI-met, UWG and CFD based on the criteria in solving EnergyPlus limitation (Y: Yes, N: No, L: Limited, -: Not applicable)

4.5.Capabilities and Limitation of Microclimate Software in Site Modelling

The table below summarizes the capabilities of EnergyPlus and microclimate software reviewed in modelling important site parameters -whether they can produce the impact of site parameters on microclimate. Overall, both ENVI-met and UWG can solve many of the limitations of EnergyPlus in modelling important site parameters.

	Site Parameters															
	Altitude				Terrain				Vegetation				Nearby Building			
Impact	Sun	Wind	Ta	RH	Sun	Wind	Ta	RH	Sun	Wind	Ta	RH	Sun	Wind	Ta	RH
EnergyPlus	-	Y	Y	-	L	L	N	N	L	N	N	N	L	N	N	-
Envi-MET	-	-	-	-	Y	L	Y	Y	Y	L	Y	Y	Y	L	Y	-
UWG	-	-	-	-	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	-
CFD	-	-	-	-	-	L	-	-	-	L	-	-	-	L	-	-

Table 4.4. Capabilities of microclimate software in modelling site parameters (Y: Yes, N: No, L: Limited, -: Not Applicable)

The EnergyPlus limitation in modelling wind impact due to surrounding terrain can be solved by following the framework proposed by Nikkho, et al. (2017) by using either ENVI-met or CFD software. This means that the application of ENVI-met possibly can solve all EnergyPlus in modelling site parameters. Meanwhile, the application of UWG must be combined with CFD software since it cannot model the wind factor on the site.

4.6.Conclusion: Workflow of Site Modelling

A site modelling workflow integrating EnergyPlus with microclimate software is proposed, as illustrated by Figure 4.3.

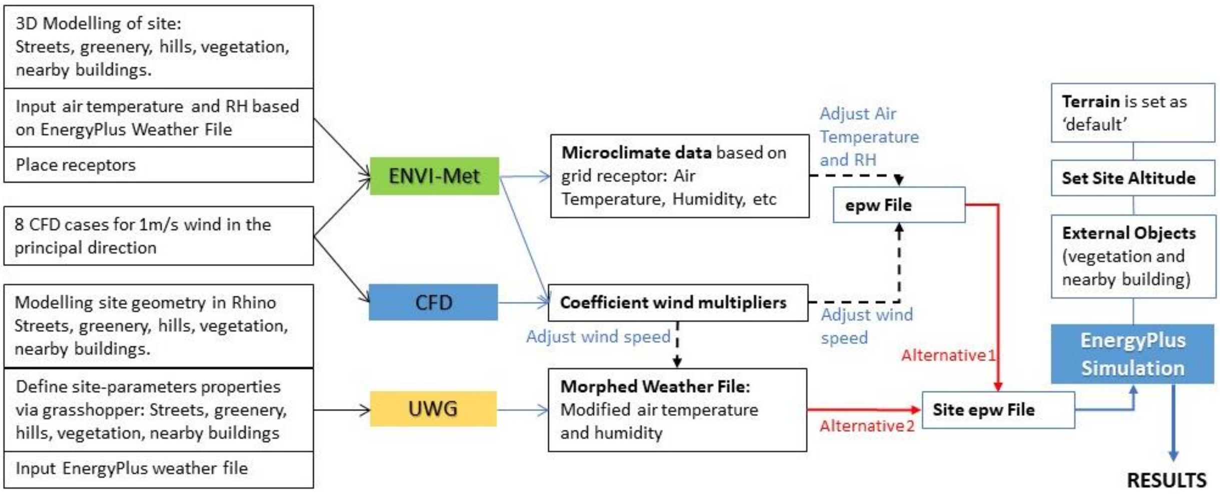


Figure 4.2. Proposed workflow: Integration of ENVI-met, UWG and CFD with EnergyPlus in modelling site

ENVI-met, UWG and CFD can each solve EnergyPlus limitations in site modelling. They are: (1) ground surface material and its contour; (2) material of nearby buildings; (3) vegetation profile; (4) external objects (terrain, vegetation and nearby buildings) providing outdoor shade; (5) external objects as windbreaks. In this case, ENVI-met can be used to model all five parameters while the UWG is utilized to model those first four parameters (1-4), which is coupled with CFD for modelling last parameter (5). The output of those software, then, can be used to modify EnergyPlus weather profile (epw). Figure 4.2 shows the workflow of the modelling site in EnergyPlus with microclimate-software integration.

4.7.Suggestion: Using ENVI-met for microclimate modelling

This research explores and focuses on the development of the Alternative 1 (see Figure 4.2) which uses ENVI-met because it can be potentially used to produce specific site-parameters impacts such as evapotranspiration from the vegetation and heating effect due to the ground and building surfaces. This can fit in the suburban context of Wellington where the house can be surrounded by various objects such as slope, tree, grass and neighbour buildings. Meanwhile, the UWG and CFD are limited to produce specific site-parameters impact. The UWG is designed specifically to calculate the generic microclimate in the urban context due to Urban Heat Island while CFD cannot generate the local air temperature due to the site object. However, the integration of those software with EnergyPlus can be investigated in future work.

The basic (free) version of ENVI-met is available through the ENVI-met website: https://www.envi-met.com/trial/. This version is limited in the domain area, parallel-computing and features presenting or visualising detail output analysis, but otherwise has the same capability as the paid science or professional version in simulating holistic microclimate model and producing its variables (see Table 4.5). The free version can be used to produce output data of hourly air temperature and RH and thus, the development of modelling site parameters using ENVI-met might produce the useful workflow that can be used globally for Urban Planners or designers.

	Basic	Student	Science	Business
Commercial use	×	×	×	✓
Parallel CPU computing	×	×	✓	✓
Open domain sizes	×	✓	✓	✓
Holistic microclimate model, vegetation modelling, Pollutant dispersion	✓	✓	✓	✓
Full 3D building design	✓	✓	✓	✓
Detailed building physics (façade temperatures and energy fluxes, microclimate at façade)	×	✓	✓	✓
Solar access analysis (sun hours, shading on ground and facades)	×	✓	✓	✓
Single walls as design elements	×	✓	✓	✓
Air pollutant chemistry	×	✓	✓	✓
Water spray simulation	×	✓	✓	✓
BioMET	×	×	×	✓

Table 4.5. The features of each version of ENVI-met (ENVI_MET, 2018)

5. ENVI-met: Microclimate software for the integration with BES

This section reviews the microclimate software: ENVI-met, which integrates with EnergyPlus. This software can fulfil many of the criteria (see section 4.2) limiting EnergyPlus limitations in modelling site parameters.

5.1. ENVI-met capabilities

"ENVI-met is a three-dimensional microclimate model designed to simulate the surface-plant-air interactions in the urban environment with a typical resolution down to 0.5min space and 1- 5 sec in time" (ENVI_MET, 2018). In ENVI-met, the microclimate model is based on grid cells, to shape the whole 3D environment. Site objects, e.g. buildings or trees, are an integral part of the grid system. Variables of microclimate data can also be produced in each grid cell and visualised through 2D or 3D graphics. Detailed microclimate data including air temperature and RH can then be produced via the receptor, a tool in ENVI-met model (SPACE) from which user can investigate any grid cell and record the value of the output variable.

In general, the microclimate model of ENVI-met calculates (ENVI_MET, 2017):

- Shortwave and longwave radiation fluxes which are influenced by shading, reflection and re-radiation from buildings and plants.
- Wind direction and speed per 3D spatial grid (the 3D CFD model is included).
- Advection and diffusion in the air within the 3D spatial grid. The ground surface and vegetation become sources or sinks for both temperature and humidity.
- Temperature calculation for each façade and roof: supporting up to three layers of materials and seven calculation points in the surface. Building surfaces act as a heat exchange with the atmosphere and humidity sources if they are greened.
- Evapotranspiration and sensible heat flux from the vegetation into the air including full simulation of all plant physical parameters (e.g. photosynthesis rate). Plants also become drag forces in the wind field.
- Heat exchange processes from the ground to the building walls and atmosphere. Soil wetness for plant water uptake is also modelled (affecting vegetation's photosynthesis rate).

Overall, ENVI-met can recreate local air temperature and humidity which are associated with the interaction between vegetation, soil and building. Secondly, it has the capability to simulate the

CFD model for generating local wind speed and direction which are affected by surrounding terrain or object.

5.2. Previous studies using ENVI-met

ENVI-met has been extensively used to investigate the impact of site properties on local outdoor microclimate in urban and built environments. Several studies have calibrated or validated the ENVI-met model by comparing simulation results with measured data. This section provides evidence for the capability and reliability of ENVI-met model based on these previous studies.

5.2.1. Site parameters impact in ENVI-met modelling

Skellhorn, et al. (2014) used ENVI-met to assess the degree to which green space and vegetation types influence local air temperature at a neighbourhood level. Six scenarios of green space in Manchester (UK) were assessed with the model calibrated against field measurements of air temperature. The modelling showed that an increase in trees could reduce mean hourly temperatures during a summer's day whereas a significant rise in air temperature was found when all vegetation was replaced with asphalt. Lee, et al. (2016) also used the ENVI-met model to estimate the influence of trees and grassland on residential microclimate area in Freiburg (Germany). They found that trees and grassland contribute to air-temperature reduction by up to 2.7^{o}C .

Wang & Zahcharias (2015) measured the influence of green space and soil on air temperature. They replaced a section of the road with vegetation and porous soil, which led to the reduction of air temperature between 0.5^{o}C – 1^{o}C. Model validation with actual weather data was also conducted in this study.

The terrain surrounding a site also impacts microclimate in ENVI-met model. Middel, et al. (2014) used ENVI-met to simulate near-ground air temperatures in different urban form scenarios in Phoenix, Arizona (United States). Their model was evaluated by comparing the simulated air temperature with observation data from a nearby weather station. They highlighted that urban model contributes more than the landscape in reducing air temperatures during the daytime. Spatial differences in cooling were also found to be strongly related to solar radiation and local shading patterns caused by dense urban forms (number, configuration and size of nearby buildings).

The research by Salata, et al. (2015) used ENVI-met to model a historic site in Rome and verified the simulation data with the field measurements. Different scenarios including variation of ground and wall material were simulated. They found that the application of high albedo materials improved the outdoor thermal comfort during winter but worsened it in the summer.

To sum up, all those studies demonstrated the capabilities of ENVI-met in modelling important site parameters discussed in the literature review (Section 2.3) including terrain, vegetation and building characeristics. There is no study related to altitude which is also considered an important site parameter – this will be discussed further in section 5.5.

5.2.2. Coupling simulation between ENVI-met and EnergyPlus

Morakinyo, et al. (2016) demonstrated the application of ENVI-met in producing microclimate data for a BES. This study combined EnergyPlus with ENVI-met to investigate the impact of tree shading in the warm-humid environment of West Africa (Nigeria). The purpose of this is to use one to solve the limitation of the other -ENVI-met is not able to simulate indoor microclimate condition while EnergyPlus cannot simulate the thermal impacts created by tree-shade. The local outdoor microclimate was produced in ENVI-met based on grid cell receptors located around the modelled building. Hourly values of local microclimate generated by receptors, such as air temperature and RH replaced the hourly value in the generic weather file (epw.). This approach was validated by comparing the simulated air temperature and RH with observational data from inside and outside the building.

Yang, et al. (2012) presented an integrated simulation method by linking ENVI-met and EnergyPlus for analysis in an urban context. This study discussed the importance of microclimatic factors in EnergyPlus such as solar radiation, longwave radiation, air temperature, RH as well as wind, and it focuses on how these factors were considered in the integration process. One of the procedures in the integration process was to modify air temperature and RH based on microclimate data produced by ENVI-met. A case study was conducted to demonstrate the proposed scheme in analysing the effect of microclimate factors on energy modelling.

Overall, these two studies reveal useful applications of ENVI-met in energy modelling. They show the output from ENVI-met which can be considered in energy calculation using EnergyPlus and demonstrate EnergyPlus can be linked with ENVI-met.

5.3. What the useful output for the energy simulation purpose

As ENVI-met generates numerous variables of microclimate data, it is essential to identify what variables can be used for the integration with EnergyPlus software. In this case ENVI-met can produce the local air temperature and RH which result from surface-plant-building interaction. Also, ENVI-met enables CFD simulation that can calculate the wind speed and direction (see section 4.1).

Hourly values of local air temperature and RH at different elevations can be generated via the ENVI-met receptor input. These numbers can then be used for weather file modification, as demonstrated by Morakinyo, et al. (2016) and by Yang, et al. (2012).

The wind speed and direction can also be produced via receptor, but thet are based on the constant wind condition as ENVI-met cannot input the wind speed and direction change. The CFD calculation in ENVI-met can be possibly utilized to generate wind speed coefficients in the eight principal directions. Then, the coefficient can be multiplied for the wind speed value in the weather file. This approach had been done by (Nikkho, et al., 2017) by using CFD software: Openfoam –(see section 4.3.3).

5.4. Another potential output from ENVI-met

ENVI-met can produce the calculation of temperature or heat flux on building facades. However, this is limited to the paid business or science version of ENVI-met. In that version, ENVI-met can generate the output of seven calculation points in the building surface. The energy balance of the outside point considers not only the changes in the meteorological variables but also the variations in reflected and emitted radiation from other buildings (ENVI_MET, 2018a).

The output of surface temperature or heat flux (w/m^2) in ENVI-met is based on the interaction of ground surface, plants and building which affect the microclimate variables as well as reflected and emitted solar radiation. If EnergyPlus can input the surface heat flux based produced by ENVI-met, then the energy calculation in EnergyPlus can be more realistic. However, it is still unknown whether the output of façade heat flux from ENVI-met can be possibly adopted to override the outside surface heat flux in EnergyPlus.

The possible EnergyPlus input which can link the ENVI-met output to the EnergyPlus input is “ExternalInterface” object via idf editor (U.S. Department of Energy, 2016e). This object involves the Building Control Virtual Test Bed (BCVTB) software which is used to develop a coupling module to transfer simulation results from different simulation programs. The BCVTB is available on http://simulationresearch.lbl.gov/bcvtb, and is freeware. A study by Yang, et al. (2012) demonstrated the application of BCVTB to develop a module for calculating the actual convective heat transfer coefficient based on the simulated air-temperature data from ENVI-met using the free (basic)version of ENVI-met. The results of this module, then, were sent back to the EnergyPlus to override original CHTC (Convective Heat Transfer Coefficient). This example shows that linking the ENVI-met output to EnergyPlus input is possible. However, as this study focuses on the development of site modelling using free software (ENVI-met basic version), this can be investigated further in different line of research.

5.5. Limitations

The ENVI-met (V.3.2) enables the user to define diurnal variations of atmospheric boundary conditions (forcing) to create a specific meteorological situation. The parameters that can be forced are air temperature and RH which are based on meteorological data (simple forcing) from a rural or suburban weather station (Salata, et al., 2016). This enables ENVI-met to have greater agreement between field measurements and simulated data (Huttner & Bruse, 2009). However, simple forcing is limited to 24 hours of input microclimate data from a weather station or observations in both the free and professional version. As a result, ENVI-met can only generate validated results of microclimate data for one day in each simulation. This means that ENVI-met cannot produce output for calculating monthly, seasonal or annual building energy use.

Furthermore, as ENVI-met can undertake CFD analysis and therefore, it can simulate the impact of trees or nearby buildings on wind condition. However, ENVI-met does not simulate a diurnal cycle for wind or wind direction changes (Middel, et al., 2014). Before simulation, the wind direction and speed at 10 m above the ground are specified in the configuration file.

Another limitation of ENVI-met is that it takes a long time when running the simulation. The previous study using ENVI-met (Skellhorn, et al., 2014) investigated the impact of vegetation types on air and surface temperatures for a neighbourhood scale. They reported that it took 72-96 hours to run the model to produce 24-hour simulation with a 4m resolution across a 180 x 140 grid. This means ENVI-met cannot be used efficiently to produce microclimate data for a long period.

5.6. Overall summary

Reviewing ENVI-met software based on the website technical documentation and previous studies demonstrates it has the capabilities to model site parameters which are limited in EnergyPlus. Moreover, this software has been validated in many studies and it is possible to integrate with EnergyPlus. The basic free version of ENVI-met is possible to use as it can produce the outputs required for generating specific local weather file. It also allows the integration of modelled site parameters between EnergyPlus and ENVI-met that can then be applied internationally.

However, the free version limited to produce detailed output analysis such as heat flux on building's façade (discussed in section 5.4), which might be useful output for the integration with EnergyPlus. This can be investigated further in different line of research.

The main limitation of ENVI-met is that it can only produce 24 hours of reliable microclimate data in one simulation, and it takes a long time to run such a simulation. This means that ENVI-met is limited in its ability to generate outputs for calculating monthly, seasonal or annual building energy use in energy simulation. However, the results of one or several days can be used as a first step to examine the importance of site parameters that cannot be modelled in EnergyPlus.

6. Method: Site Modelling in ENVI-met

This section explores ENVI-met software for BES site modelling. It starts from the parametric study to identify the important basic inputs in ENVI-met model. This can be useful information to determine the standard setting for further tests -Parametric study for different site scenarios and integration process with EnergyPlus. The results from site scenarios test can give the answer how important the site parameters (that cannot be modelled in EnergyPlus) are and conclude whether the application of site weather as produced by ENVI-met is essential in energy simulation.

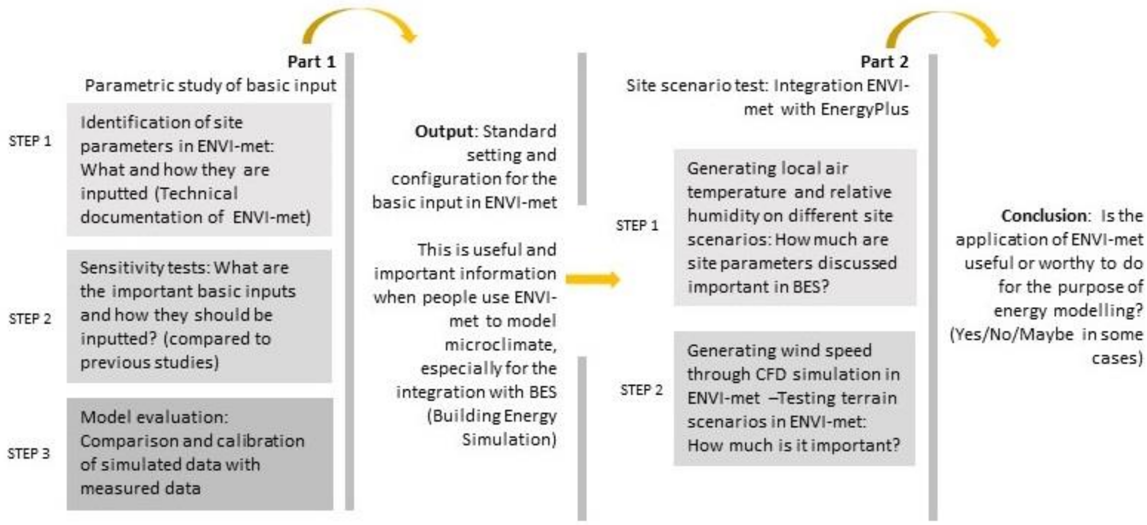


Figure 6.1. Series of steps of ENVI-met investigation in modelling site.

7. Parametric test and model evaluation of ENVI-met basic input

Although a number of studies have used ENVI-met for urban design and thermal comfort studies, this software is still under development, and full documentation is not yet available. Before using ENVI-met to investigate the importance of site parameters, an understanding of how the model responds to changes in basic input parameters is essential -How these inputs influence simulation results. It is also important to ensure an ENVI-met model produces reasonable results (validation) before using the model to examine microclimate parameters (Salata, et al., 2016).

A study by Salata, et al. (2016) evaluated the basic input parameters in the ENVI-met model and proposed procedure simulation. However, this study used the previous version (3.1) where the test was based on two LBC (Open and Cyclic). The new version (4.3.2) provides an additional LBC (Forced) which produces improved results (Huttner & Bruse, 2009) and has better stability (ENVI_MET, 2017a).

Therefore, the parametric test and model evaluation proposed in this research focuses on the Forced LBC. This aims to establish the standard setting and configuration of basic input which is relevant for ENVI-met V.4.3.2. These results can then be used for further simulation in investigating the importance of site parameters.

7.1. Key question: The influence of basic input on the simulation results

Basic inputs in ENVI-met are investigated to assess how much they affect the simulation results. In this case, the significant difference of ENVI-met output is defined as a difference that can lead to more than 5% change of house heating energy calculation in EnergyPlus. Therefore, there are five key questions that should be answered which relate to the basic inputs:

7.1.1. The importance of grid size setting

As explained in section 5.1, the 3D microclimate model in ENVI-met is established by grid cells. Thus, it is important to decide what is the most appropriate grid size for simulations in this study. Salata, et al. (2016) found that the finest grid (1m) produces values in closer agreement to the measured data while a bigger grid size produces much faster computational times. This suggests that the model with the 1m grid size is preferable as it can produce more accurate results.

However, as this study uses the Basic Version of ENVI-met (V.3.2), the number of grid cells is limited in the domain area to only 100x100x40. A grid size of 1m can create the site object with the finest resolution but cannot create a larger site than 100m by 100 m. For example, a 2m grid would allow for a 200m by 200m site. Also, as the receptor data is defined as being at the grid centroid (ENVI-met Forum, 2018), a grid size of 1m leads the receptor to the closest distance with the building facades where, from the perspective of energy modelling, the microclimate condition interact with the building surfaces. Contrastingly, while a bigger grid size allows simulation for larger area, it might not be able to precisely model the size of the object. Salata, et al. (2016) also discovered that the bigger grid size (applied in the same size of the domain area) leads to the quicker computational time in the simulation.

In this case, some sub-questions, which should be answered, are:

1. How much does the grid size affect the results of the simulation?
2. To what degree are results sensitive to receptor distance from the building facades? For example, the 1m grid size can locate the receptor 0.5m from the building façade while the 5m grid size locates it 2.5m from the building facade. Are they significantly different?
3. How is the computational time in ENVI-met simulation affected by different grid sizes?

These questions are investigated through a parametric study discussed in sections 7.3.2, 7.3.4 and 7.3.4 to determine optimal grid size.

7.1.2. Simulation duration for model stability

Some studies (Morakinyo, et al., 2016) (Salata, et al., 2016) (Yang, et al., 2012) used a 72-hour duration simulation utilizing the last 24 hours of simulated data to analyse the calibration of their ENVI-met model with measured data. In general, this measure aims to refine output data affected by problems during the initialization (Morakinyo, et al., 2016). Skellhorn, et al., (2014) showed that the 72-hour simulation allowed for model stability, with simulation results converging towards measure data in the third day. However, except Yang, et al. (2012), these used ENVI-met V.3 with only two types of LBC: Open and Cyclic which only input initial air temperature and RH for starting conditions.

ENVI-met V.4.3.2 provided the new Forced LBC which enables creation of hourly air temperature and RH profiles based on measured data via the "Simple Forcing" tool. Those values are input 2m above the ground of the model for a single 24-hour cycle.

So, the key question here is:

"How different are the simulation results of each day over a three-day (72h) iteration simulation?"

If the Forced LBC can produce consistent or similar results in each day, then the 72-hour simulation is not necessary, and computational time can be saved. This question is explored in section 7.3.4 by comparing the simulation results of the three iteration days.

7.1.3. The importance of wind input

ENVI-met cannot model wind speed and direction change. This might be an issue since wind conditions can frequently change especially in a windy region such as Wellington. Wind conditions influence the heat flow on the site through convection, which can lead to cooler or warmer air temperature in a specific location. Therefore, in this case, the important question is:

"To what degree does does wind speed and direction affect the air temperatures as simulated by ENVI-met?"

This question is investigated through a parametric study in section 7.3.4. The answer to this question can be used to determine the wind input setting the further tests.

7.1.4. Domain area

Every site object, such as trees, slopes and soils interacts with the microclimate system. Numerous site objects in a larger domain area might produce a major or minor influence on microclimate data generated by a specific receptor. This raises the question:

"How much does the domain area affect the simulation results and how large is the ideal domain area for an ENVI-met model?"

This was investigated through model evaluation in section 7.4.

7.1.5. Soil condition

The creation of the ENVI-met base model must be not influenced by site parameters such as hills (terrain feature), vegetation, or nearby buildings. Nevertheless, soil type is one terrain feature that must be defined.

The soil type in ENVI-met model might have a significant influence on the simulated data depending on its material. For example, soil type asphalt may cause elevated air temperatures while grass may have a cooling effect in ENVI-met model. The soil type may lead inaccuracies in the simulation results as it is based on the default values. Thus, the key question that should be asked:

"Is the default soil type input in ENVI-met acceptable with respect to simulation accuracy?."

This was explored through model calibration in section 7.4.

7.2. Site parameters in ENVI-met

The three levels of climatic condition (macroclimate, mesoclimate and microclimate) were discussed in section 2.1. This section reviews the site parameters defined in ENVI-met from perspective of climatic condition.

ENVI-met uses the portion of the weather data file (.epw) which represents the location and meteorological background. It provides a tool to locate the site based on the latitude and longitude coordinates, which impacts on the simulation solar radiation. Thus solar radiation in ENVI-met is internally generated, not based on the measured data. Other meteorological background data such as RH and air temperature are also inputted via the "Simple Forcing Tool" from the weather data file. Wind speed and direction above 10m can also be inputted in the basic meteorological settings.

ENVI-met also provides properties for site objects such as trees, building surfaces, and soils. For example, the albedo value of building surfaces or vegetation can be modified in the ENVI-met database. Their geometries can be created and defined via the "SPACE" tool. Every site object in ENVI-met interacts with the microclimate system, and thus, they can influence a particular point within the site model. For example, at the microscale, a tree model can cool the air temperature nearby due to its shade, but it does not affect the air temperature 10m away. At the mesoclimate level, numerous tree models can significantly influence air temperature over a large area due to evapotranspiration effects.

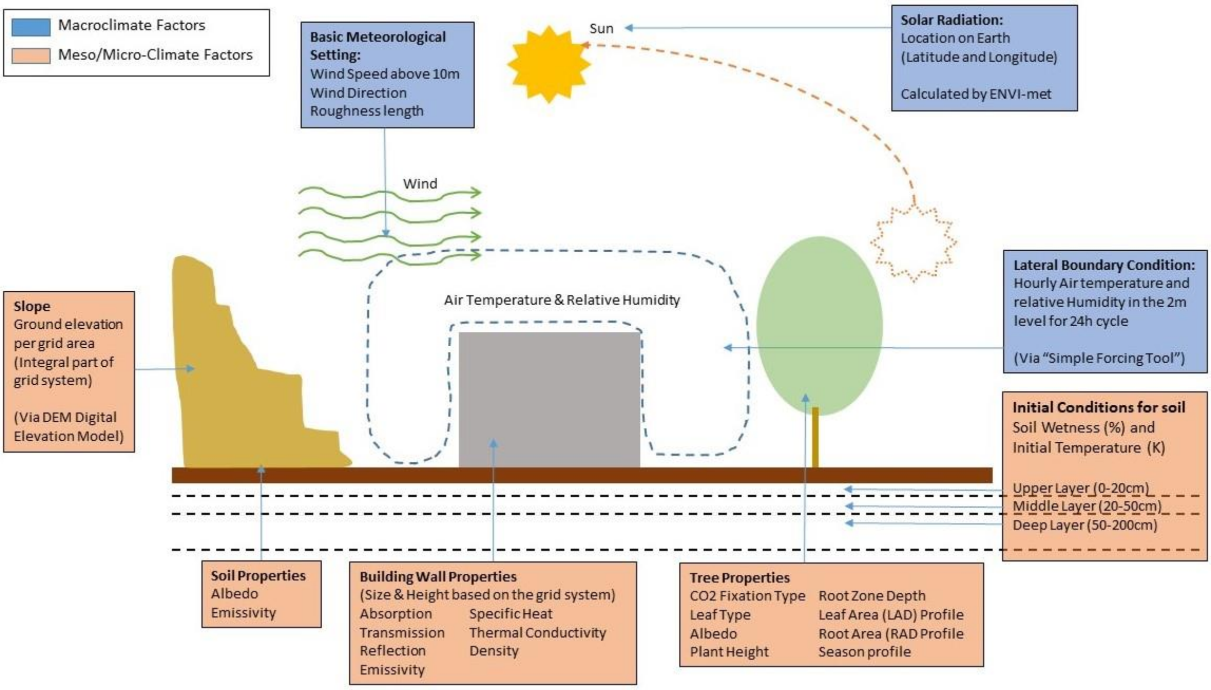


Figure 7.1. Site Parameters in ENVI-met from Climatic Level Perspective

Figure 7.1 illustrates how the three levels of climatic conditions are defined in ENVI-met. Overall, macroclimate factor inputs such as solar radiation, air temperature, RH and wind condition are required for ENVI-met. Specific site parameters such as trees or buildings are considered as meso- and micro- climate factors because they might have a big or small influence on microclimate depending their numbers in the broader area surrounding the modelled site.

7.3. Parametric study of basic input

This section presents the parametric study to follow up the key questions in the previous section (7.1)– whether the grid size and wind input are influential for ENVI-met simulations. The output of this will be used to develop the setting and configuration for the Base model for the parametric study of site scenario. The computational time and error in this test are reported to evaluate the ENVI-met application. The simulation was conducted in PC with an Intel Core i7 4790s processor, with 8 CPUs and 16 GB RAM.

7.3.1. Input and model settings of the tested model

In the "SPACE" tool, site location was set for Wellington at a latitude of -41.29 and a longitude of 174.78. The construction R-Values for the EnergyPlus house model were determined using NZS 4214:2006, which provides the information of thermal resistance (R-Value) of building components and elements (Standards New Zealand, 2006). The simple building model is modelled with the same design as the EnergyPlus preliminary test building (10mx5m in length and width with 3m in height) and is placed in the centre of the site. So, in this case, the building model is created by 5x10 of horizontal grid cells and the building height was set at 3m (See the figure below) -The building volume is 150m^3. Three receptors were placed outdoors in the middle of the west (a1), north (a2) and east (a3) wall of the north zone., with the receptor output at 1.5m from the ground.

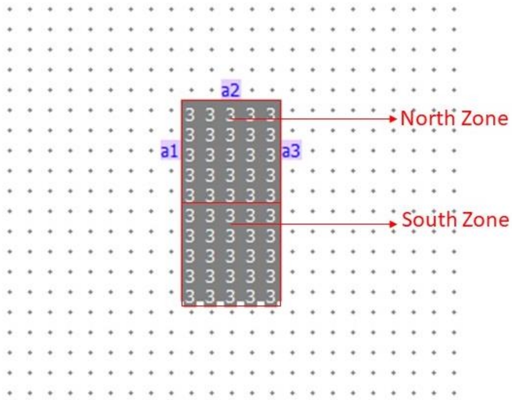


Figure 7.2. The base model for the parametric study of base input

For the initial simulation test, it is assumed the site is in an inland, suburban area (but at a higher altitude than at the coastal area). So, the “simple forcing” tool input uses the hourly air temperature and RH values for 2016 from the suburban weather station in Kelburn, Wellington. A date of 20th June was chosen for the input as it is in the middle of the winter, close to winter solstice, and had no rainfall. The simulation was set for 72 hours, starting from 00:00 19th to 23:00 on 21st June. From the climatic perspective in ENVI-met, those three days have a similar condition in terms of sun exposure. This allows a comparison of simulated data between each day to document the difference for investigating one of the key questions in section 7.1.2. The output of the last 24 hours was analysed as recommended by Skellhorn, et al. (2014).

The wind speed and direction (basic meteorological setting) were set simply to the average wind speed and direction: 12ms^{-1} and 245^{o} (south-west), following previous research (Salata, et al., 2016).

7.3.2. Parametric study for the grid size

This test investigates whether the grid size affects the computational time and the simulation results. As the grid size increases, the domain area becomes larger, and this might lead to longer computational time. Besides, the grid size is highly likely to influence the simulated data from the receptor since the grid size defines the receptor position.

7.3.2.1. Grid scenarios and process

The grid sizes from 1 to 5m are tested. All tested model used the same grid number (50x50x25). The size of house models cannot be created exactly the same as due to the grid size difference. Thus, the house model for this test was adjusted to have a similar size which is 150m^3 of volume. Table 7.1 shows the 1m did not complete processing as it generated errors, while the 2 m grid generated errors but auto corrected.

Grid Size	**Domain Area**		**House Model**						**Process and Computational time**
	Grid Volume (m^3)	Area Volume (m^3)	Blocks (LxH)	Block Area (m^2)	Floor Area (m^2)	Height (m)	Volume calculated (m^3)	Volume reported (m^3)	
1m	1	62,500	10x5	1	50	3	150	150	Error
2m	8	500,000	3x4	4	48	3	144	192	Errors but Auto fixed- 53h 17min
3m	27	1,687,500	2x3	9	54	3	162	162	Success -16h 33 min
4m	48	3,000,000	1x3	16	48	3	144	153.6	Success -16h 3 min
5m	125	7,812,500	1x2	25	50	3	150	150	Success -16h 10 min

Table 7.1. Simulation Process of Grid Size test (wind speed 12ms^{-1})

The grid sizes of 3 ,4 and 5m were successful in simulation process without any numerical errors, and they took a similar time for simulation. This indicates that the grid size does not impact on the computational time.

However, an error emerged in the running of the model with 1m and 2m grid size - “floating point error”. This error is due to the numerical instability during the initial turbulence calculation. The technical page of ENVI-met website notes the software uses a Turbulence Kinetic Energy (TKE) Model to predict the air turbulence. There are three types of equation in this model: (1) distribution of the kinetic energy in the air depending on production, advection, diffusion and destruction, (2) Dissipation Rate of TKE (ε or eps), and (3) Turbulent Exchange Coefficient (Km) which is a result of first and second equation. The third equation (Km) is used as input data for the next calculation cycle. Therefore, if Km becomes unstable, the TKE-ε equation system will be unstable too, and the instability repeats in the next cycle (ENVI_MET, 2017b).

In general, there are two main causes of these errors:

1. Technical problem. This problem is related to CPU or WINDOWS used for ENVI-met simulation. “Under some conditions, ENVI-met produces nonsense running under WINDOWS. This results mainly in Errors in Floating point calculations when the initial turbulence field is calculated or other abnormal termination during the initialization. This problem can sometimes overcome

by turning off the computer and reboot it and then restart ENVI-met. Also, there might be a thermal problem with your CPU." (ENVI_MET, 2017d)

2. Problem with the model configuration. This can be solved by changing the basic input based on the suggestion from ENVI-met machine after running the model.

In this case, there are three successful models: the grid of 3,4 and 5m. Thus, the error is not caused by the technical problem related to the CPU or WINDOWS. ENVI-met suggested: (1) increasing area domain or grid size, or (2) turning off the buoyancy term.

Related to the first suggestion (1), it is clear from the table above that the bigger grid-size models (3, 4 and 5m) are successfully simulated. The second suggestion (turning off the buoyancy term) was not applied in this study as this will change the default settings in the model configuration (via "configwizard") related to the LBC and turbulence model equation. As shown in the configwizard display, changing the default settings is recommendedonly for the advanced user.

At practical way to fix that error is by changing the wind speed to below 6ms^{-1} (ENVI-met Forum, 2018). This approach was also used by a previous study (Yang, et al., 2012) which purposely set a low value of wind speed (almost zero) to avoid numerical problem during simulation. Therefore, additional grid-size tests with low wind speed (0.8ms^{-1}) were also conducted.

Grid Size	Domain Area		House Model						Process and Computational time
	Grid Volume (m^3)	Area Volume (m^3)	Blocks (LxH)	Block Area (m^2)	Floor Area (m^2)	Height (m)	Volume calculated (m^3)	Volume reported (m^3)	
1m	1	62,500	10x5	50	50	3	150	150	Success -14h 20 min
2m	8	500,000	3x4	4	48	3	144	192	Success -17h 24 min
3m	27	1,687,500	2x3	9	54	3	162	162	Success -17h 12 min
4m	48	3,000,000	1x3	16	48	3	144	153.6	Success -17h 2min
5m	125	7,812,500	1x2	25	50	3	150	150	Success -14h 45 min

Table 7.2. Simulation Process of Grid Size test (wind speed 0.8 ms^{-1})

All grid sizes modelled with a wind speed of 0.8ms^{-1} were successfully simulated. The grid size of 2,3 and 4 meters were simulated at the same time (using three instances of ENVI-met on a single computer), and they took longer computational time than others. The 1m and 5m grids with 0.8ms^{-1} of wind speed took a shorter time than with 12ms^{-1}. This indicates that wind speed input affects the computational time: low wind speed is shorter in computing simulation.

7.3.2.2. Grid Size Issue

There was an issue related to building size validity. This was found in the model of 2m and 4m grid size where the calculated building volume is not the same as that reported by ENVI-me. The largest difference of building size was found in the model of 2m grid size, which differs by 48m^2. The table below compares calculated building volume of the different grid-size models with that reported by ENVI-met. An additional model of grid 6m size was created and checked to see its building volume and compete with other models. In general, even-number grid size does not report a valid building volume.

Grid Size	House Model						Size Validity
	Blocks (LxH)	Block Area (m^2)	Floor Area (m^2)	Height (m)	Volume calculated (m^3)	Volume reported (m^3)	
1m	5x10	1	50	3	150	150	Yes
2m	3x4	4	48	3	144	192	No
3m	2x3	9	54	3	162	162	Yes
4m	1x3	16	48	3	144	153.6	No
5m	1x2	25	50	3	150	150	Yes
6m	1x2	36	72	3	216	172.8	No

Table 7.3. Building Volume Calculation in ENVI-met

In ENVI-met, the building block is an integral part of the grid system and the lowest cell (near ground) is divided into a 5 sub-cells subgrid (ENVI-met Forum, 2018). Thus, only the model with 1, 3 and 5m grid-size can have 3m of building height while even-numbered grid sizes cannot be used to model the building height of 3m. However, only the grid size of 1 and 5m can create a precise size for the building.

7.3.2.3. Results

The three following line charts (Diagrams 7.1, 7.2 and 7.3) compares the air temperature the three receptors produced by the models with 12ms-^{1} of wind speed with the grid size of 3m and 5m. The grid sizes of 1 and 2m with 12ms^{-1} of wind speed were excluded due to the errors as well as the 4m grid-size model due to the issue in volume calculation.

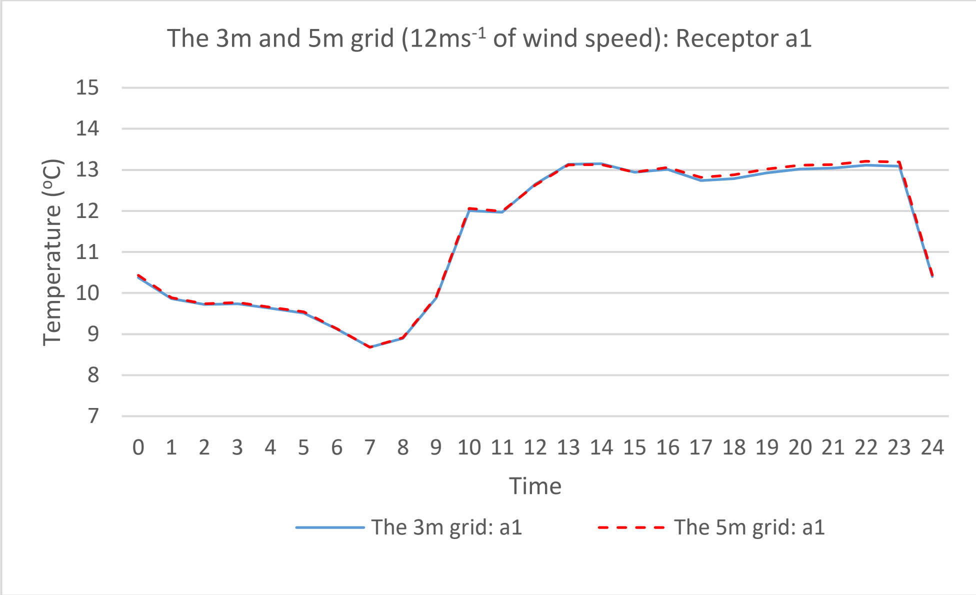


Diagram 7.1. Hourly air temperature West receptor (a1): the grid of 3 and 5m (wind speed: 12ms^{-1})

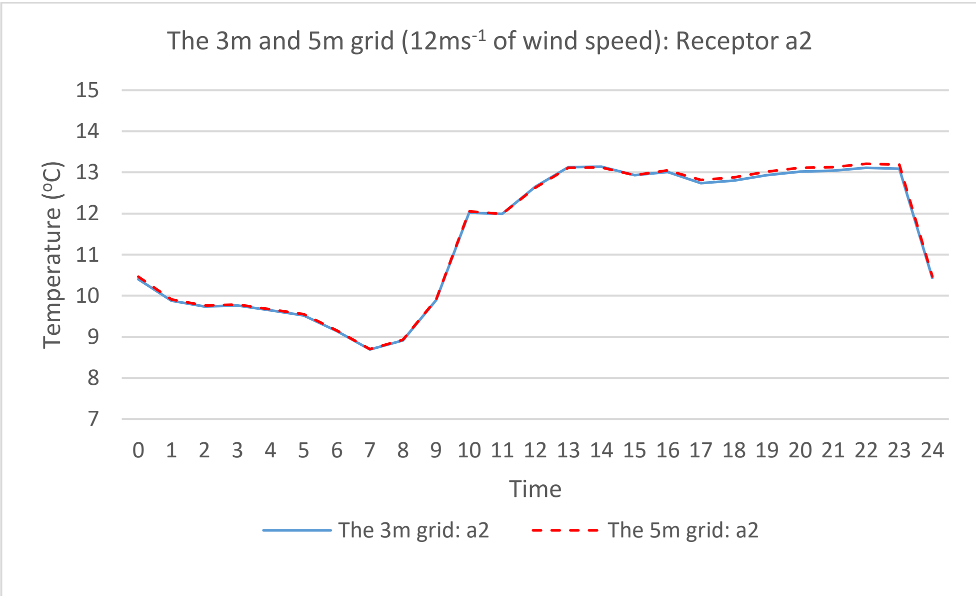


Diagram 7.2. Hourly air temperature North receptor (a2): the grid of 3 and 5m (wind speed: 12ms^{-1})

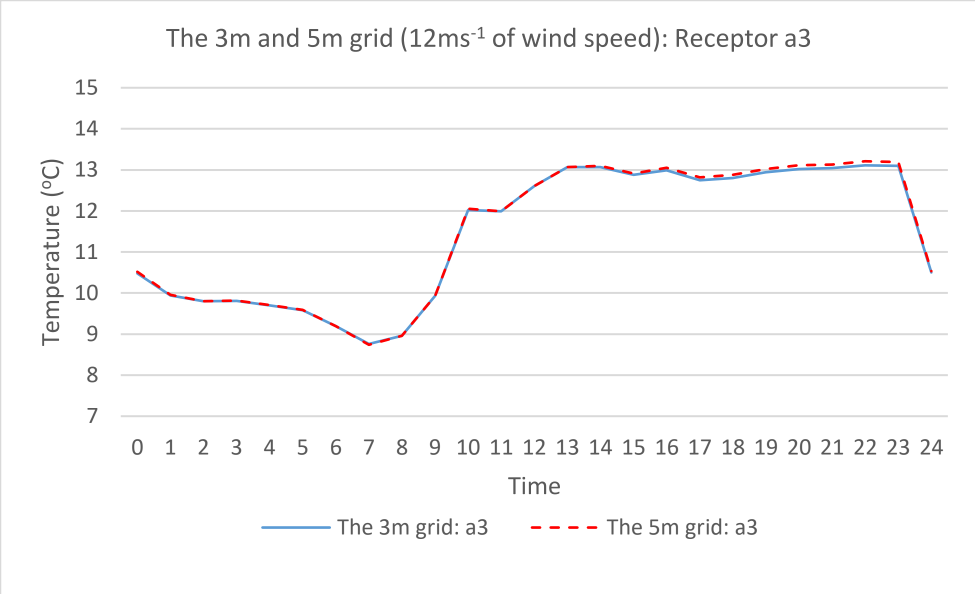


Diagram 7.3. Hourly air temperature East receptor (a3): the grid of 3 and 5m (wind speed: 12ms^{-1})

In general, the 3m and 5m grid-size model produce the same hourly air temperature trend in the three receptors. The biggest difference between the two models is about 0.1^{O}C, which occurs between at 21.00-23.00 in all receptors.

Diagrams 7.4, 7.5 and 7.6 show the hourly RH trend between the 3m and 5m grid in the three receptors. As would be expected, the RH between the two models is also similar as there is no significant gap of air temperature between the two models. The difference between the two models is no more than 1% where the grid of 3m is slightly higher than the 5m is from 00.00 until 08.00.

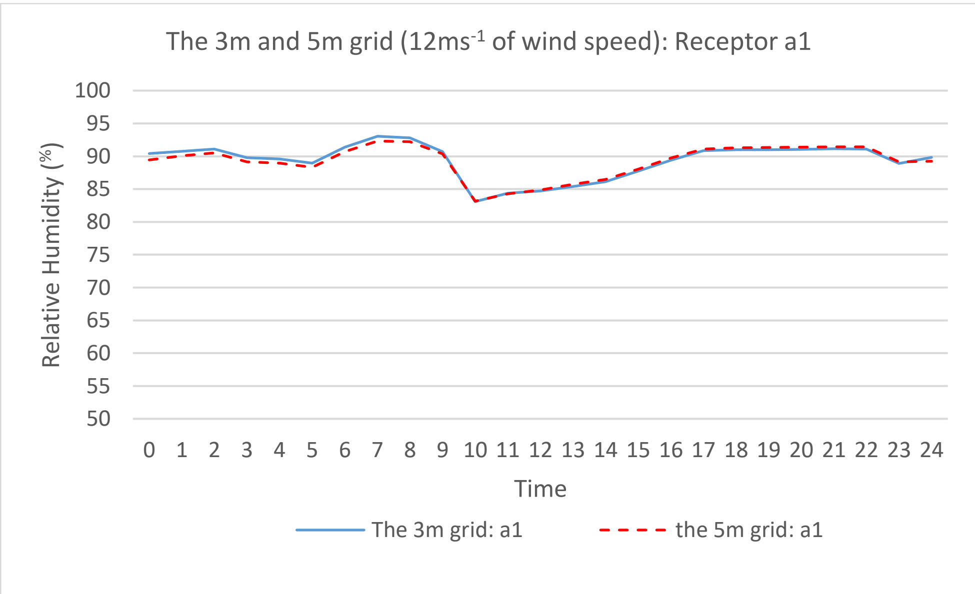


Diagram 7.4. Hourly RH West receptor (a1): the grid of 3 and 5m (wind speed: 12ms^{-1})

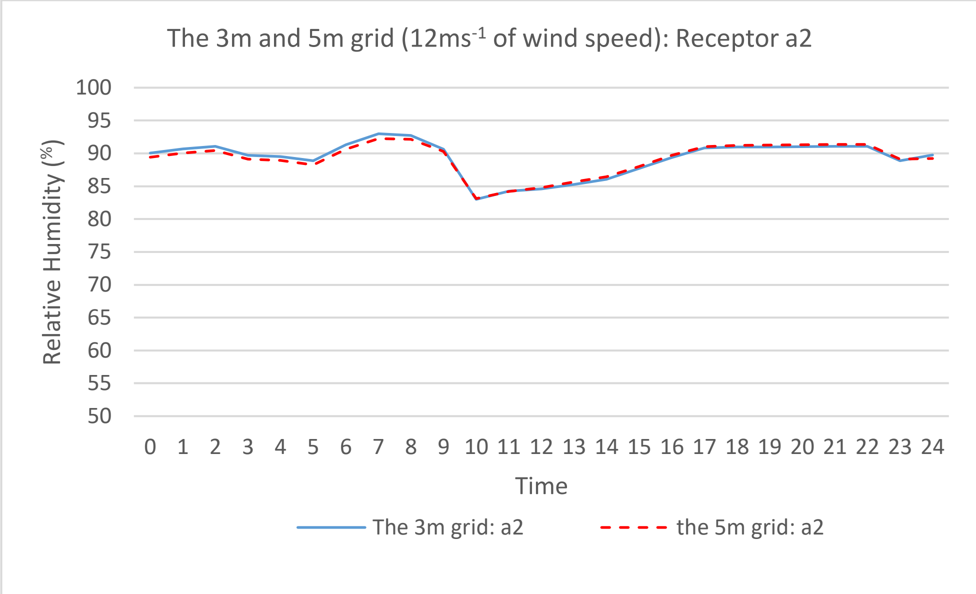


Diagram 7.5. Hourly RH North receptor (a2): the grid of 3 and 5m (wind speed: 12ms⁻¹)

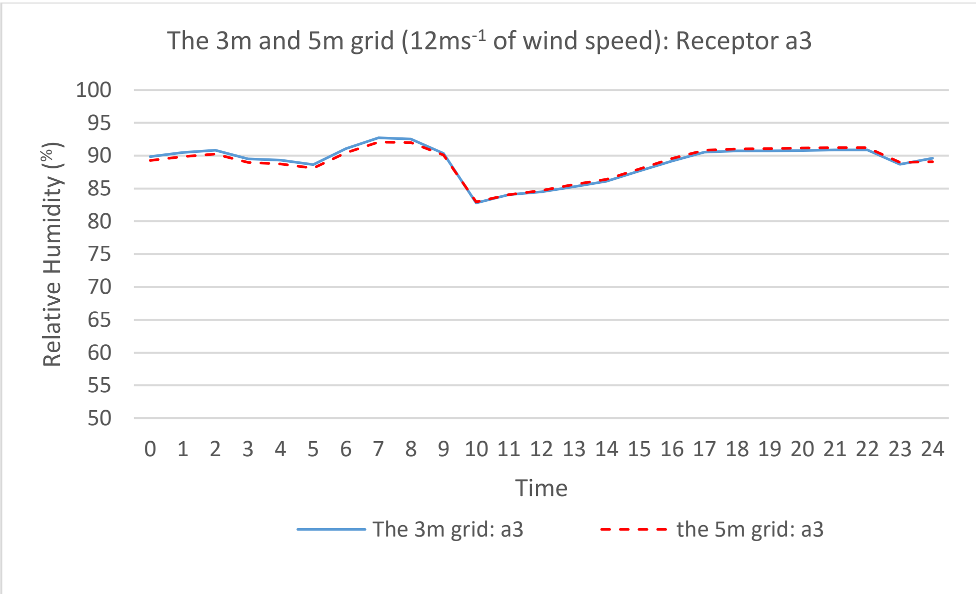


Diagram 7.6. Hourly RH East receptor (a3): the grid of 3 and 5m (wind speed: $12ms^{-1}$)

Diagrams 7.7, 7.8 and 7.9 show the hourly temperature for the West (a1), North (a2) and East (a3) receptor in the 1, 3 and 5 grid-size models with $0.8ms^{-1}$ of wind speed. The grid size of 2 and 4m are excluded due to the volume-calculation issue. Overall, there is an obvious gap between those three models compared the results from grid cells with $12ms-^{1}$ (Figure 7.1, 7.2 and 7.3). The simulated data of air temperature between 3m and 5m are not too different where the biggest gap is about 0.3°C. Meanwhile, the difference between the 1m and 5m is much bigger, which reaches about 1°C.

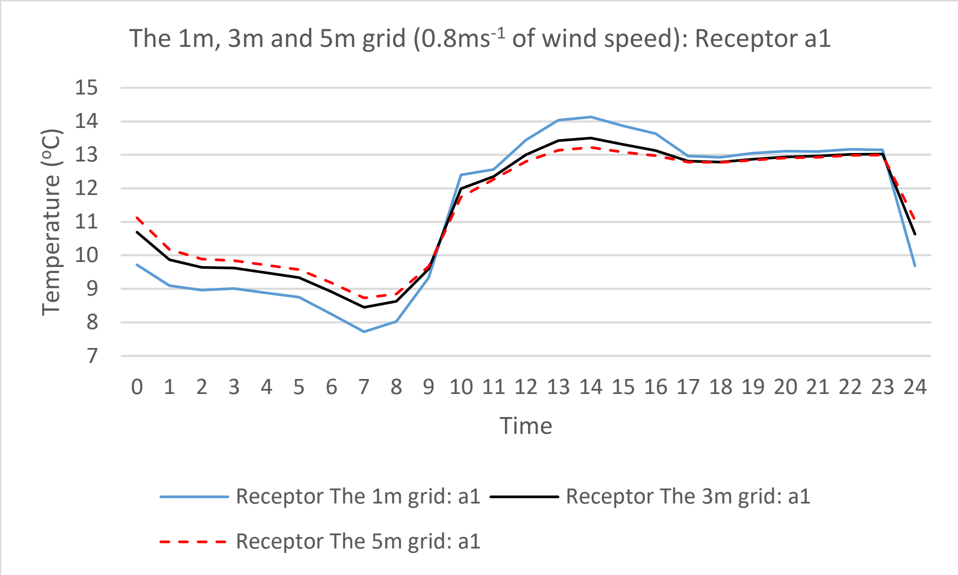


Diagram 7.7. Hourly air temperature West receptor (a1): the grid of 1, 3 and 5m (wind speed: 0.8ms^{-1})

There biggest difference in the receptor a1 is between the 1m and 5m grid, which averages 1°C during the beginning of the day (00.00 to 08.00) and 0.9°C around the midday (13.00-15.00). In this case, the grid size of 1m has a lower temperature in the morning while it is higher around the midday.

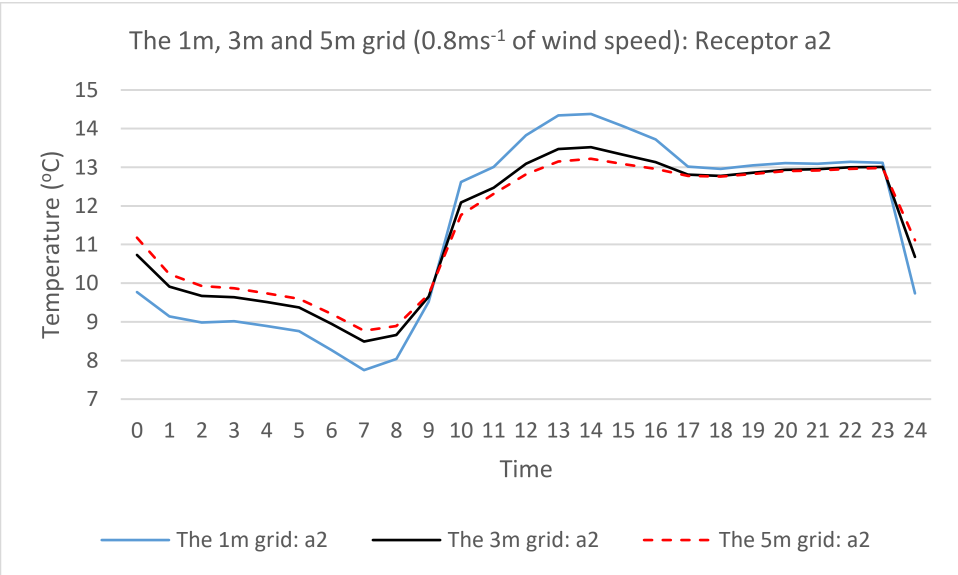


Diagram 7.8. Hourly air temperature North receptor (a2): the grid of 1, 3 and 5m (wind speed: 0.8ms^{-1})

The similar trend also emerges in the receptor a2 with slightly bigger difference by averagely 1.1°C from 13.00-15.00 between the 1m and 5m grid. In addition, the three models have a similar value in the evening, from 17.00 until 23.00, with the difference no more than 0.3°C.

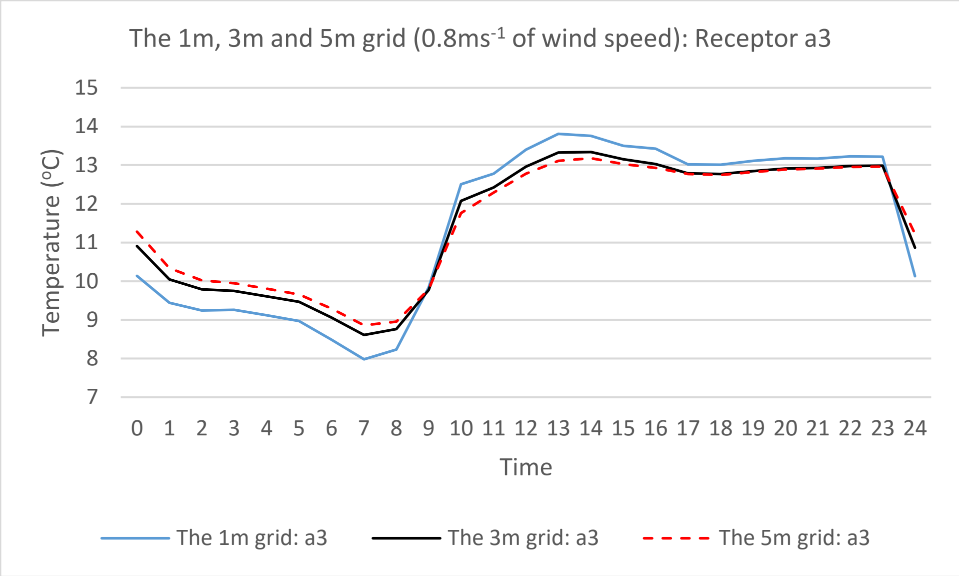


Diagram 7.9. Hourly air temperature East receptor (a3): the grid of 1, 3 and 5m (wind speed: 0.8ms^{-1})

The difference between the 1m and 5m grid in the East receptor (a3) is smaller compared to other receptors. In average, the difference is 0.8°C from 00.00-08.00 and 0.6°C from 13.00-15.00.

On the other hand, the three models have a similar trend of hourly RH with the difference no more than 5% (see Diagram 7.10, 7.11 and 7.12). However, the difference between the grid 3m and 5m is narrower compared to the grid 1m.

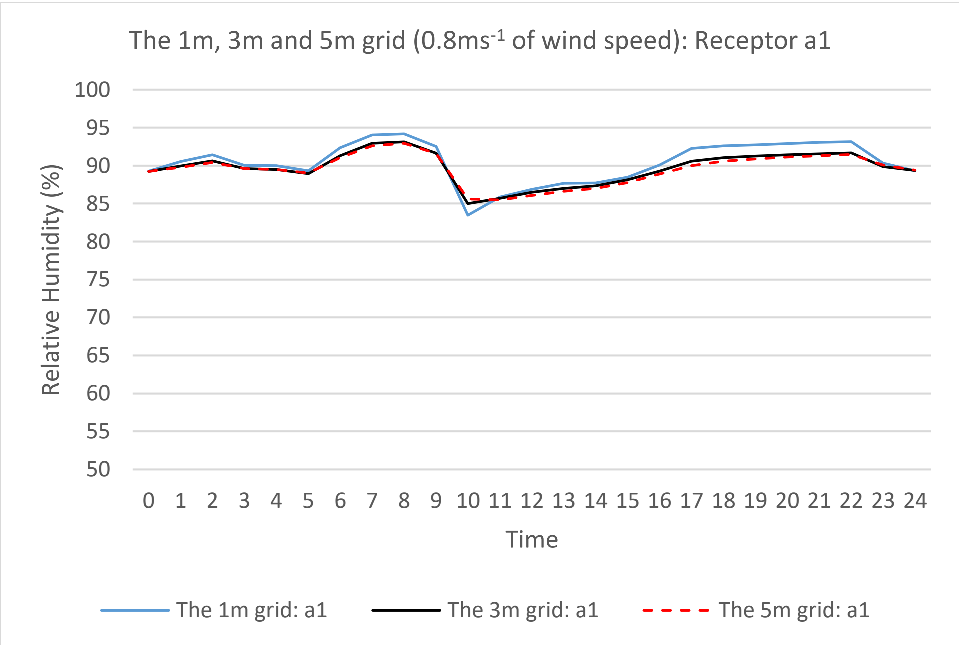


Diagram 7.10. Hourly RH West receptor (a1): the grid of 1, 3 and 5m (wind speed: 0.8ms^{-1})

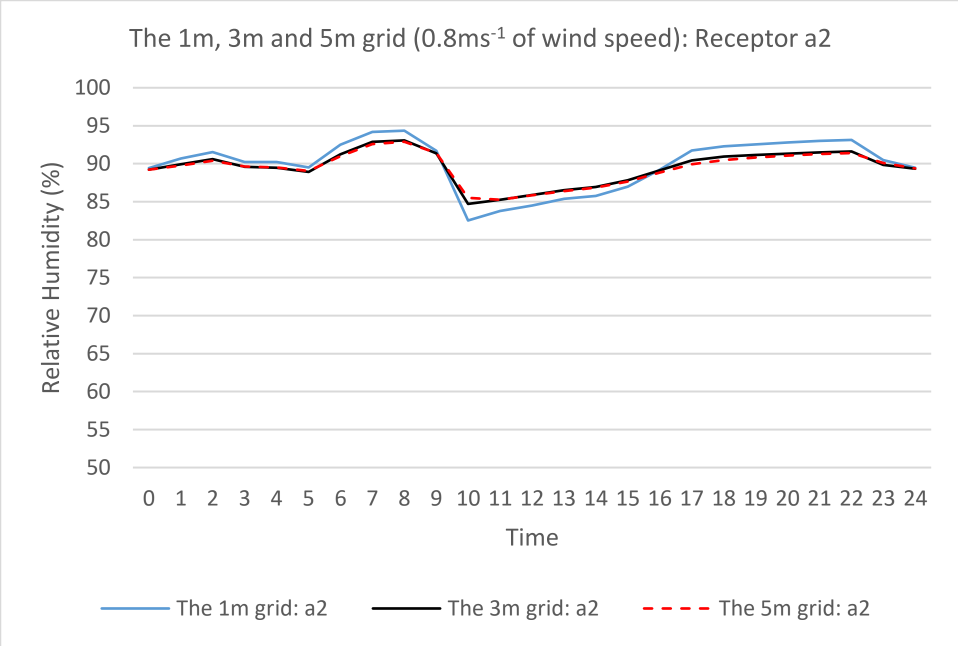


Diagram 7.11. Hourly RH North receptor (a2): the grid of 1, 3 and 5m (wind speed: 0.8ms^{-1})

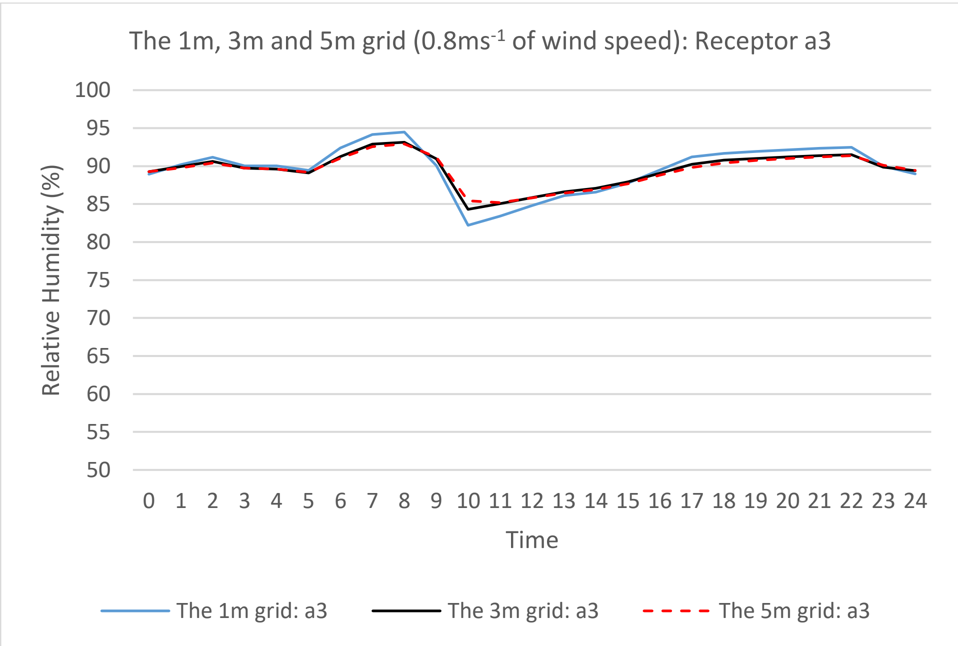


Diagram 7.12. Hourly RH East receptor (a3): the grid of 1, 3 and 5m (wind speed: 0.8ms^{-1})

7.3.2.4. Overall summary: findings and anomaly

Diagrams 7.1-7.12 show there are similar results for the 3m and 5m grids both in the low (0.8ms^{-1}) and high wind-speed model (12ms^{-1}), although the difference between both models is no more than 0.3°C. However, there is an anomaly in the results for the 1m grid-size model with 0.8ms^{-1} (Diagram 7.7, 7.8 and 7.9) since this model has a much bigger difference of air temperature (1.2°C) compared to the other grid-sizes. This anomaly should be addressed as it leads to the difference which might significantly influence the BES calculation. This raised the question: ***How significant is the air temperature difference in house energy modelling?*** This is addressed in section 7.3.3.

There are also two possibilities associated with the grid cells why the 1m grid has a larger difference compared to other models:

1. Receptor distance. As the receptor gives microclimate data in the grid centroid, the change of grid size affects the receptor location. The model with grid 1m has the receptor with 0.5m from the building facades while other models are greater distance: 1.5m for the 3m grid and 2.5m for the 5m grid. This distance is highly likely to affect the simulation results as the receptor which is closer to the building object gets more interaction to the building surface - It influences the heat transfer its surrounding by absorbing or re-radiating the heat.
2. Site size. With the same number of grid cells, the site size of the 1m grid-size is much smaller than that of the 5m grid-size (62,500 m^3 & 7,812,500 m^3 respectively). As the building and receptors are in the centre of the site, they are surrounded by the ground surface and atmosphere grid cells. Much more ground objects and atmosphere grid cells surround the model with a 5m grid size. These might influence the simulation results of the microclimate model.

Those two possibilities are investigated further in section 7.3.4

7.3.3. Significance of air temperature difference in house energy modelling

This section follows the question from section 7.3.2.4 to investigate the significance of air temperature difference. The parametric tests in EnergyPlus were conducted by inputting different modified weather files based on the microclimate data produce by ENVI-met. It tests three microclimate data resulted from the grid-size test in the previous section (7.3.2.3): The 1m, 3m and 5m grid with 0.8ms^{-1} of wind speed in the receptor a2 (see Diagram 7.8) since their trend comparison show the biggest difference compared to other results.

This test applies the design of house model based on the section 3.3.1.1 (see Figure 3.3). It calculates house heating energy for both the North and South zones while the previous test (section 3.3) only calculated the North zone. This is because the test in section 3.3 specifically examines the impact of site parameters, and the North zone (living room) was considered to be able to highly interact with microclimate condition affected by the change of site parameters (see

Section 3.3.1 and 3.3.1.1). The parametric tests in this section focus on the air-temperature significance for the house generally.

The internal gains for lighting and equipment used the same input in the Table 3.4. The house model is assumed for three people (1.5 in each zone), with75W per person with 60% availability during daytime (7:00-23:00) and 100% during night time (23:00-7:00) (BRANZ, 2007). Based on the modelling method in NZS 4218:2009, the minimum temperature should be maintained at 18°C from 7am to 11pm and at 16°C overnight, with a maximum temperature of 25°C. The set point for cooling was set at 25°C and 24°C for the natural ventilation. In this case, the ventilation air-flow rate was defined by the natural ventilation input: 'WindandStackOpenArea' object where the flow rate is determined by wind speed and the thermal stack effect, along with the area of the opening being modelled (U.S. Department of Energy, 2016b). For that input, the openable area for natural ventilation was set to 5% of the total area per each zone (1.25m^2) with the fraction of 0.125 of the total openable area, which based on the minimum requirement of Clause G4 of the NZBC (Ministry of Business, Innovation and Employment NewZealand, 2008) and scheduled from 7am to 11pm.

The Diagram 7.13 shows hourly air temperature difference between the 1m and 3m grid compared to the 5m grid, and the Table 7.4 compares the house heating energy use in EnergyPlus for 20th June based the three different microclimate data from the Diagram 7.8 (1m, 3m and 5m grids with 0.8ms^{-1} wind speed).

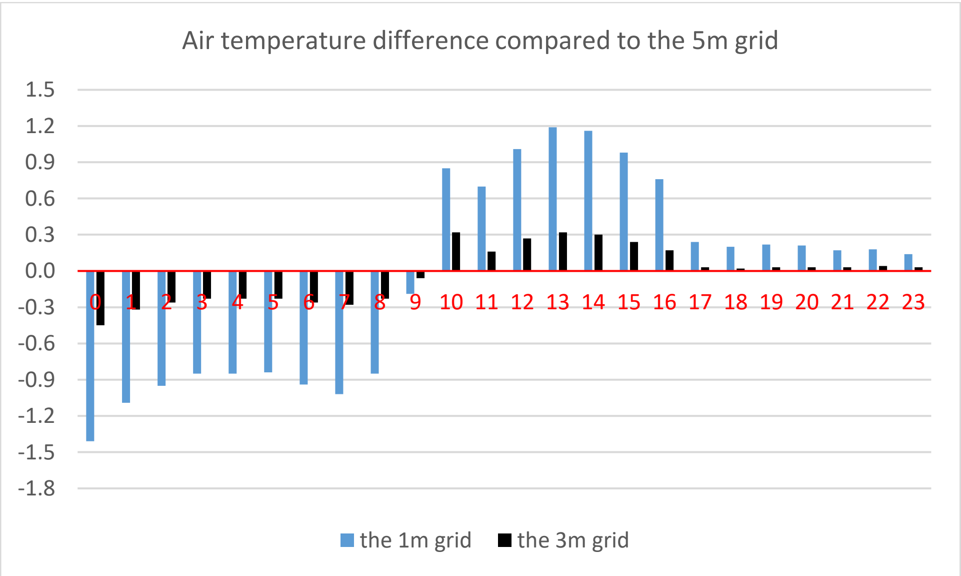


Diagram 7.13. The air-temperature gap between the 1m and 3m grid compared to the 5m grid

Model	Temperature difference (day / night)	Energy use (Wh)	Difference (compared to the 5m grid)
The 1m grid	~1°C	6644	9.7%
The 3m grid	~0.3°C	6217	2.6%
The 5m grid	Base	6059	-

Table 7.4. The house heating energy use for 20th June based on the output from the 1m, 3m and 5m (wind speed: 0.8ms-1)

The average overnight (midnight to 8 am) and daytime (10 am to 4pm) temperature difference is 1°C for the 1m grid compared the 5m grid, and for the 3m grid is 0.3°C. The average air-temperature difference of 1°C between the 1m and 5m grid leads to 9.7% difference of energy consumption for space heating. For the 3m and 5m grids, the difference is only 2.6% due to 0.3°C difference. The difference 1°C is significant as it affects the calculated heating-load by nearly 10% (as defined in Section 7.1).

An item of interest is that the 1m grid has the highest heating load while it has the warmest temperature during the day. The higher heating load of the 1m grid is due to heating during the cooler part of the day (00.00-08.00)

Diagram 7.14 shows the hourly heating load for 20th June for the 1m, 3m and 5m grid. The space heating in all models is not activated around the midday until late evening, from 10.00-22.00, as the house model can passively reach the minimum setpoint (18°C) during that time.

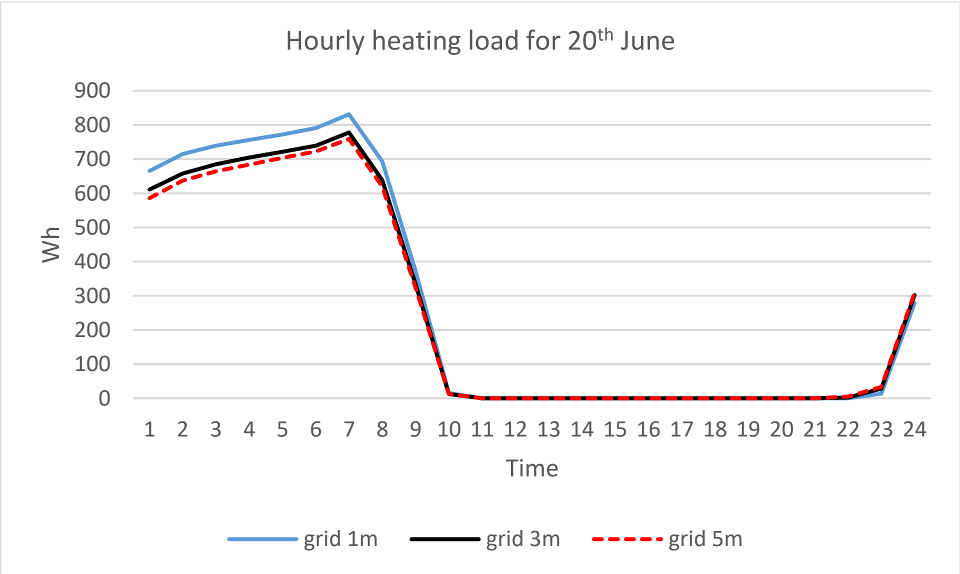


Diagram 7.14. Hourly heating load for 20th June for the the 1m, 3m and 5m grid (wind speed: 0.8ms-1)

The reasons for the difference are investigated in the next section (7.3.4).

7.3.4. The impact of site size and receptor distance

This section investigated two possibilities discussed in the previous section (7.3.2.4) - the bigger difference of the 1m-grid output data compared to the 3m and 5m grid. The additional testing was conducted to investigate the impact of receptors distance and site size on simulation result, which is associated with the grid-cell size.

7.3.4.1. Model development

There are two models with 0.8ms^{-1} of wind speed developed to have the same receptor distance from building surface and the site size:

1. The model of the 1m grid-size with by adding the three receptors at a distance of 2.5m from the building façade, giving the same receptor distance from building's facade as for the 5m grid.
2. The model of 5m grid-size by reducing the number of grid cells to (10x10x5). This makes the total grid size become the same as the 1m grid-size (62,500 m^3).

Figure 6.3 illustrates the two additional models. The additional receptors (a4, a5 and a6) are inputted in the 1m grid and their distance from building facades (2.5m) are the same as those of the 5m grid (a1, a2 and a3). The results of those two models were compared to the model of 5m grid-size with 7,812,500 m^3 of volume, which are input in the same wind speed (0.8ms^{-1}).

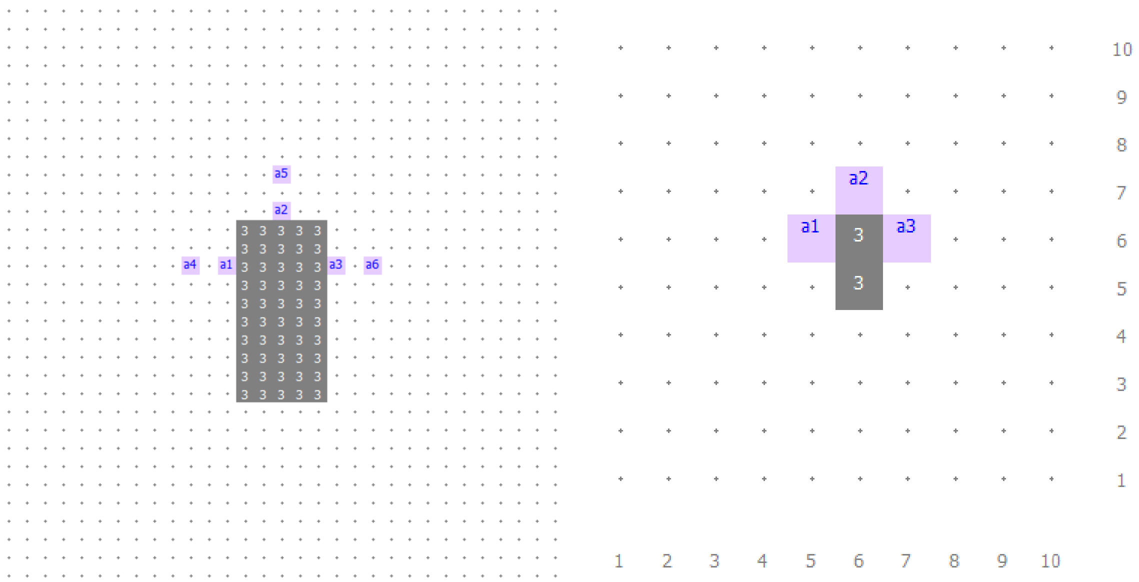


Figure 7.3. Left: additional receptors in 2.5m from facades; Right: The grid of 5m with 10x10x5 of grid cells

The 1m and 5m grid size are further developed with the different number of grid cells to investigate the impact of site size. Table 7.5 shows the model development for the 1m and 5m grid-size with different domain area as well as the computational time. Overall, the more grid cells in the model, the longer computational time.

	The 1m grid-size		The 5m grid-size	
Site size (m^3)	Cells	Computational time	Cells	Computational time
62,500	50x50x25	15h 49min	10x10x5	20 min
350,000	100x100x35	94h 45 min	20x20x7	1h 23 min
1,687,500		-	30x30x15	4h 17 min
4,000,000		-	40x40x20	8h 24min
7,812,500		-	50x50x25	14h 45 min

Table 7.5. The model developed for the 1m and 5m grid size with different site size

The increase of site size in the 1m grid size is not possible as the ENVI-met basic version cannot model more than 100x100x40 cells.

7.3.4.2. Results and discussions

Diagrams 7.15, 7.16 and 7.17 compare the simulated air temperature for the 1m and 5m grid in 62,500 m^3 domain area as well as the 5m grid in 7,812,500m^3. In general, all simulated data produced by the model with 62,500 m^3 have the biggest difference by no more than 0.3°C from midnight to 8am and 0.6°C in the midday (10am to 3pm). Moreover, the 5m grid with 7,812,500m^3 of domain area has much bigger difference compared to other three output data, which are by averagely 1°C in that time.

Based on the section 7.3.3, those three-output data from the model of 62,500m^3 can be considered as similar as their difference will not significantly affect the results of heating load in energy simulation. Meanwhile, the output of the 5m grid with 7,812,500 m^3 of domain area can lead to significant difference of heating load in energy calculation compared to other output data.

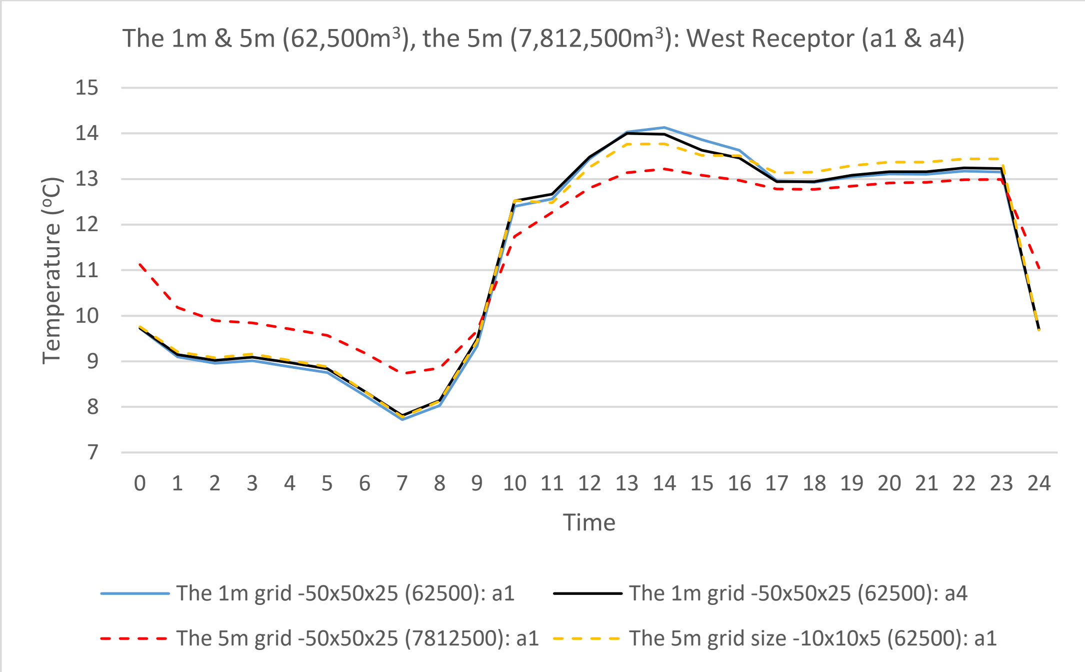


Diagram 7.15. Hourly air temperature the receptor a1 between the 1m and 5m grid-size (wind speed: 0.8ms^{-1})

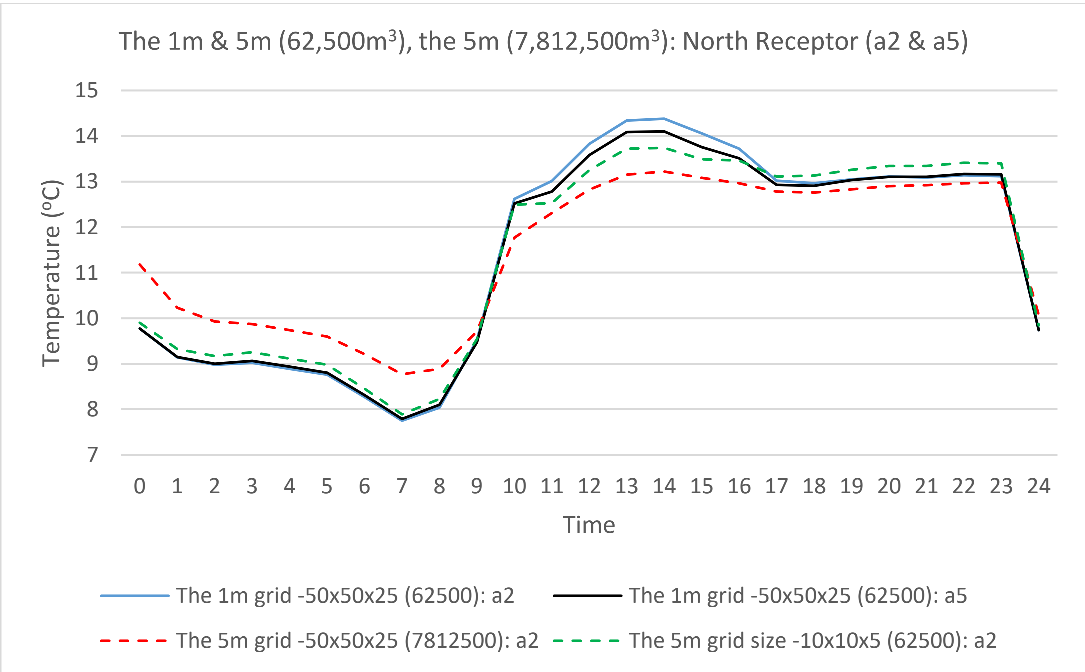


Diagram 7.16. Hourly air temperature the receptor a2 between the 1m and 5m grid-size (wind speed: 0.8ms^{-1})

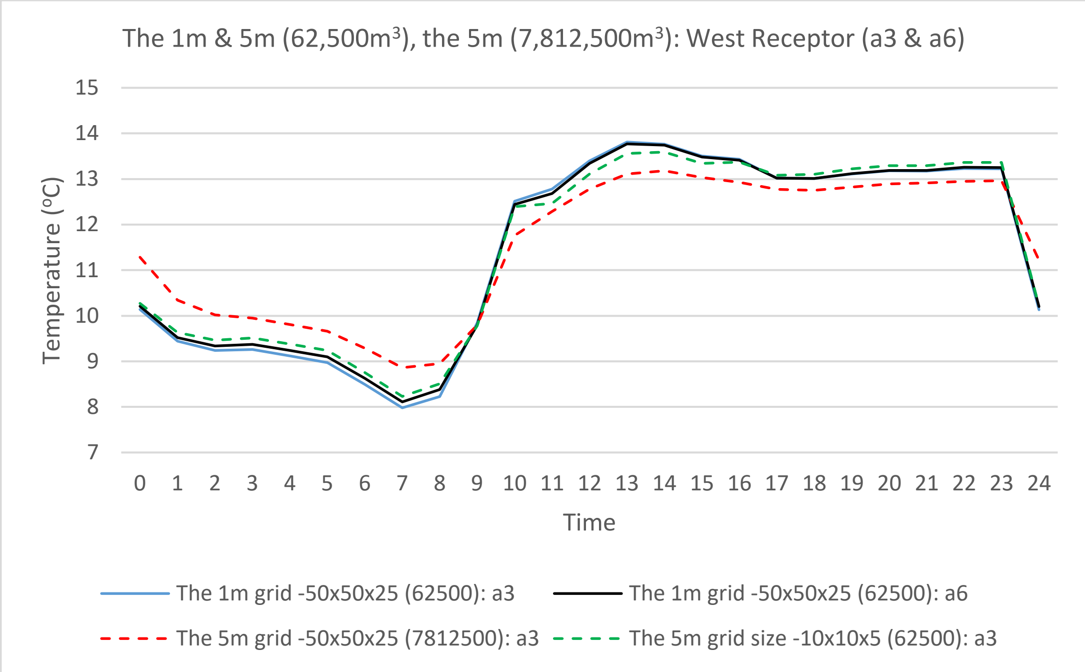


Diagram 7.17. Hourly air temperature the receptor a3 between the 1m and 5m grid-size (wind speed: 0.8ms^{-1})

The receptors a1, a2 and a3 in the model of 62,500m^3 consistently have higher daytime temperature (10.00-15.00) compared to other receptors in the same direction. This is likely because of the building's façades heating the adjacent air temperature nearby.

The following six diagrams (7.18-7.23) shows the simulated air temperature in the 1m grid size with different site size, using receptor data in the same location. In general, the medium (62,500m^3) and large model (350,000m^3) have the similar trend with the biggest gap no more than 0.3^{o}C. Such a difference will not significantly impact on the heating load calculation in energy simulation (discussed in section 7.3.3).

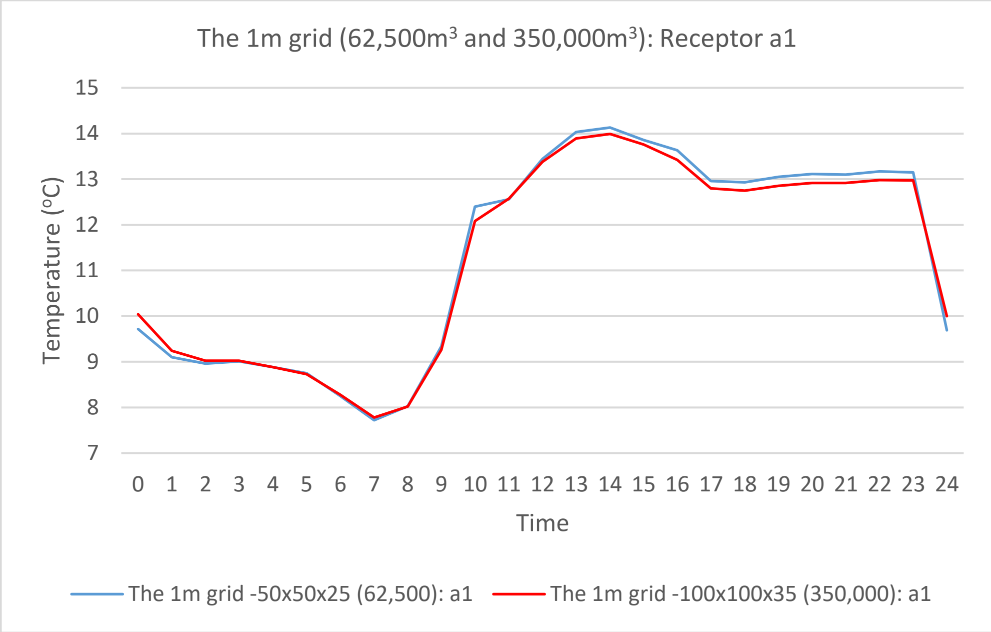


Diagram 7.18. Hourly air temperature the receptor a1 (west) in the 1m grid with different site size

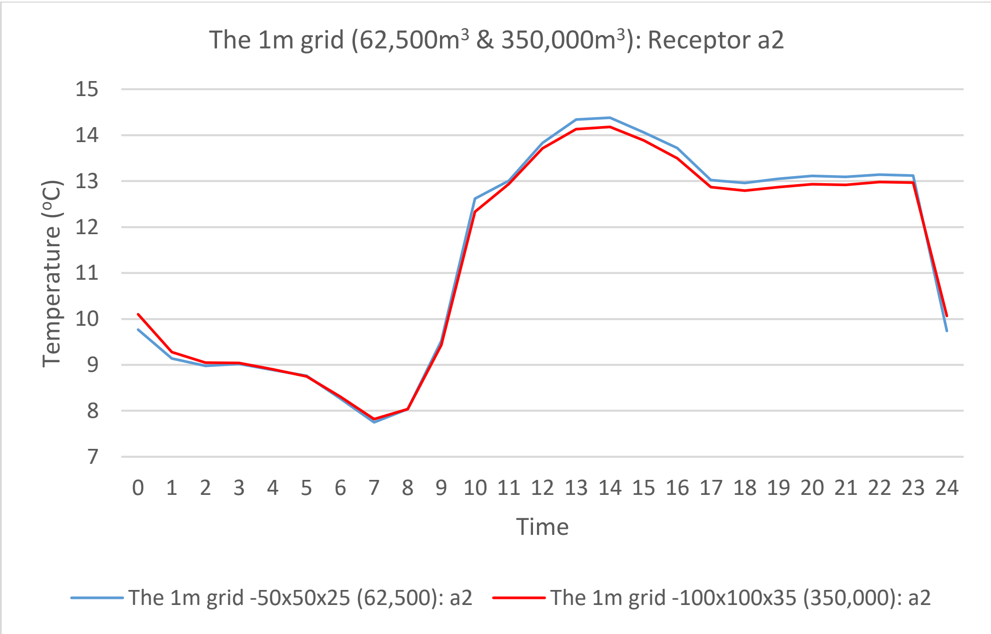


Diagram 7.19. Hourly air temperature the receptor a2 (north) in the 1m grid with different site size

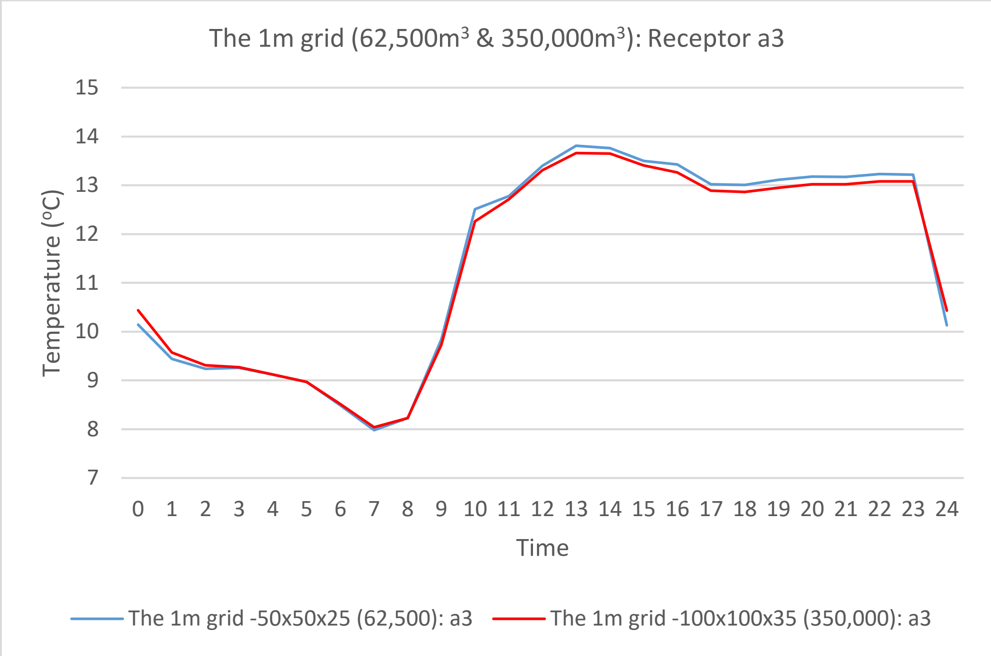


Diagram 7.20. Hourly air temperature the receptor a3 (east) in the 1m grid with different site size

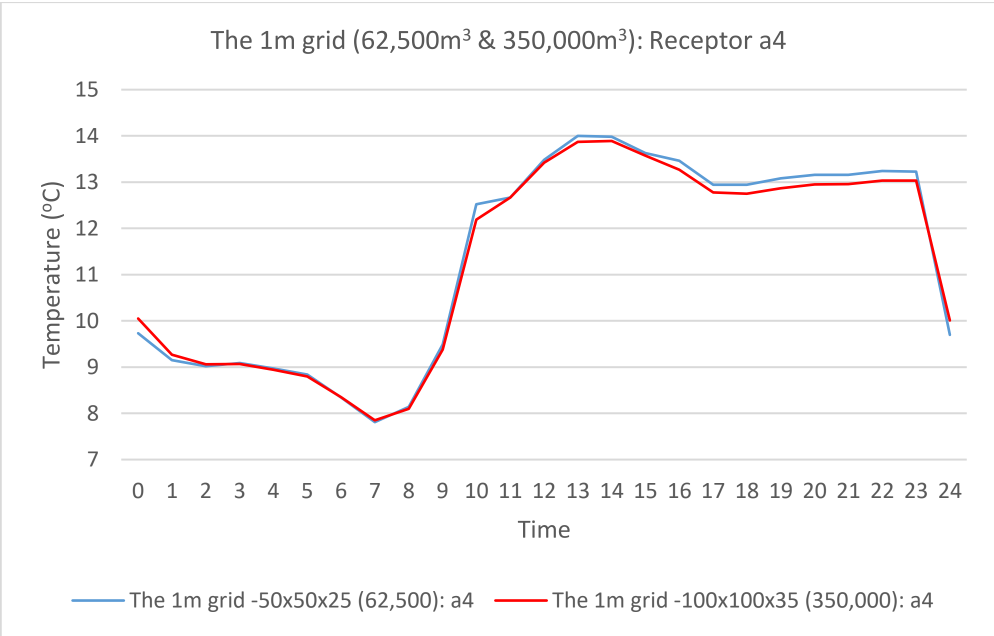


Diagram 7.21. Hourly air temperature the receptor a4 (west) in the 1m grid with different site size

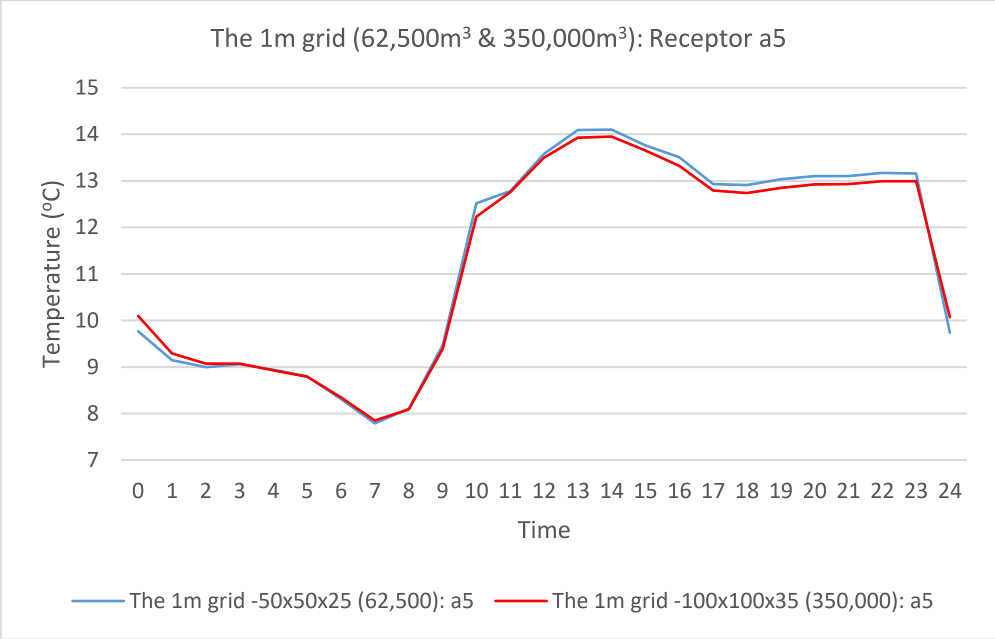


Diagram 7.22. Hourly air temperature the receptor a5 (north) in the 1m grid with different site size

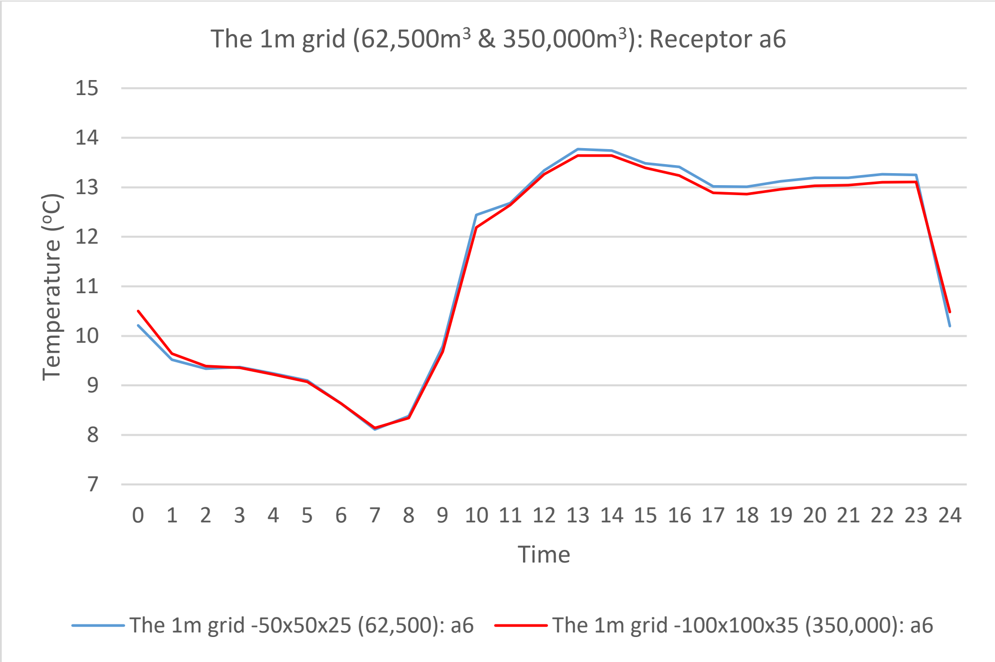


Diagram 7.23. Hourly air temperature the receptor a6 (east) in the 1m grid with different site size

Diagrams 7.24, 7.25 and 7.26 shows the data for the 5m grid with different site sizes. In general, the smallest site has the lowest temperature from midnight to 9am and the highest temperature afterwards until 11pm whereas the biggest site is the opposite (highest from midnight, lowest from 10am).

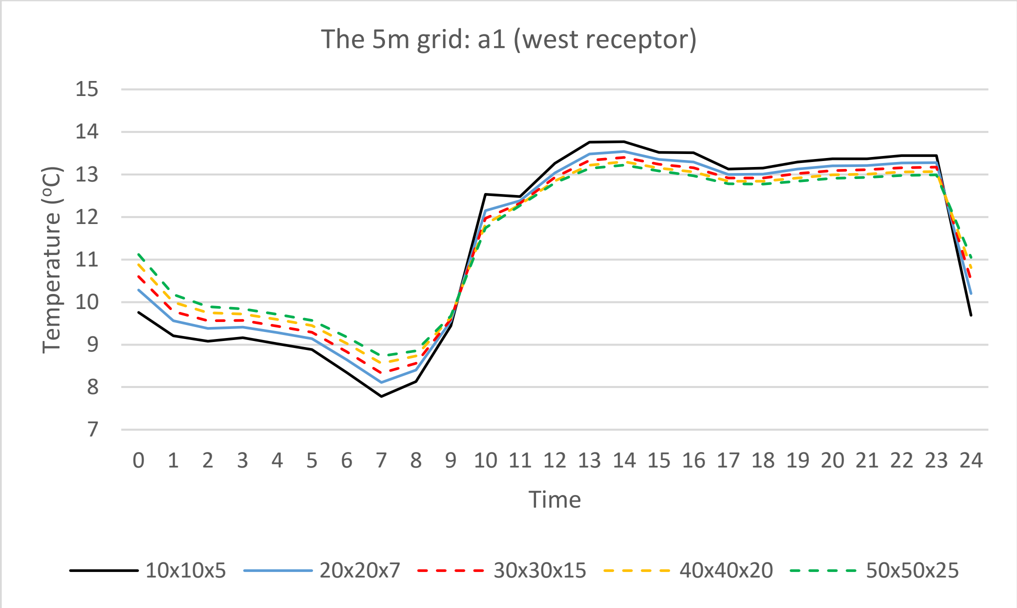


Diagram 7.24. Hourly air temperature the receptor a1 (east) in the 5m grid with different site size

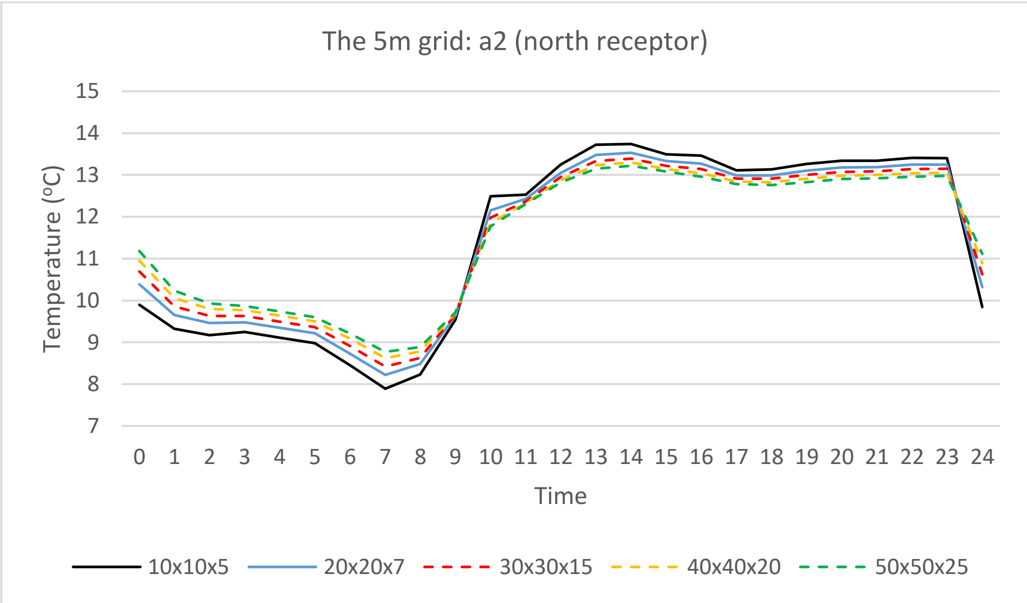


Diagram 7.25. Hourly air temperature the receptor a2 (north) in the 5m grid with different site size

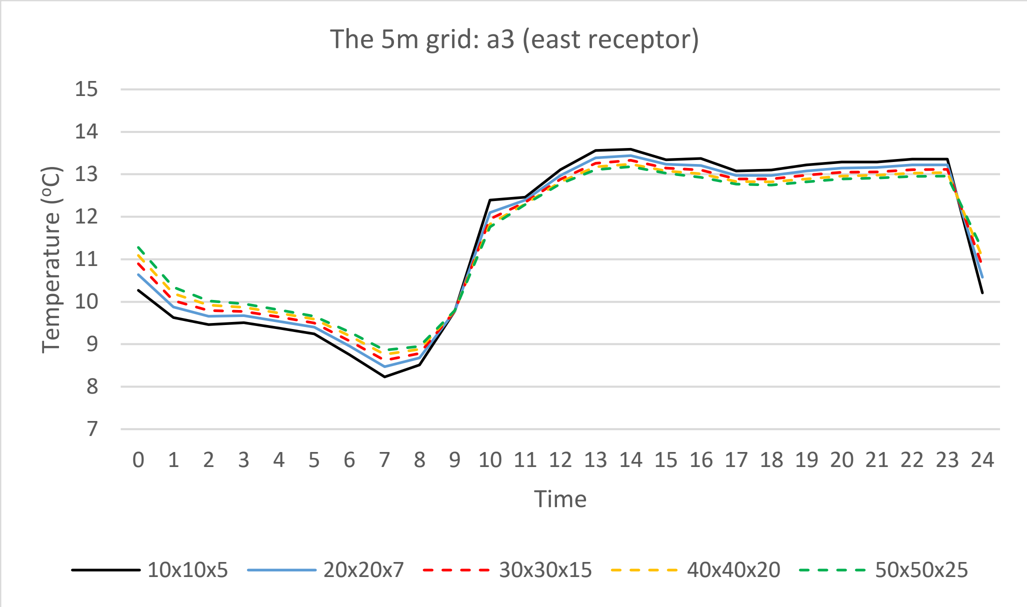


Diagram 7.26. Hourly air temperature the receptor a3 (west) in the 5m grid with different site size

The difference between the simulated data for the 5m grid gradually increases with the increase of site size. The biggest difference is between the smallest site size (10x10x5 cells/ 62,500 m^3) and the largest site size (50x50x35 cells/ 7,812,500 m^3), which averagely reaches by 0.9°C from midnight to 8am and 0.5°C from 10am to 11pm for receptors a1 and a2. This difference is considered significant as it can significantly impact on the results of energy simulation by almost 10% (discussed in section 7.3.3).

The comparison between three receptor data in different directions is made in order to see the difference of temperature in the daytime which might be influenced by orientation (building shade) and heating effect from building's façade. The following diagrams (7.27-7.30) compare the simulated air temperature from three receptors in different in orientation (west, north and east) in the 1m grid-size model with different domain area. Overall, the three receptors which are closest to the building facades (a1, a2 and a3) have bigger difference in the daytime (10.00-16.00) than those (a4, a5 and a6) located 2.5m from the building façade both for the small (62,500m^3) and large site (350,000m^3).

That difference demonstrates that the closest receptor from façade in the 1m grid is affected by the heating effect of the building surface. In this case, the North receptor (a2) has the biggest temperature in the daytime as the north facade receives more solar radiation during the winter. The East receptor (a3) has higher air temperature by about 0.1°C than the west receptor from 10-11am as the East façade gets more sun exposure in that time than the east façade. Then, it becomes much lower than the West receptor (a1) from 1-3pm by about 0.3°C as the west façade receives more solar radiation in that time.

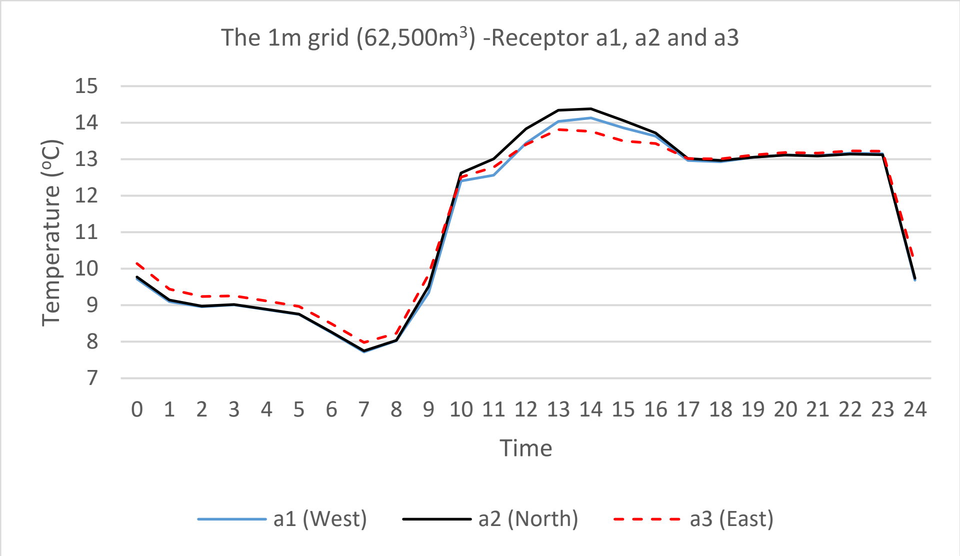


Diagram 7.27. Hourly air temperature receptor a1, a2 and a3 for the 1m grid (62,500m³)

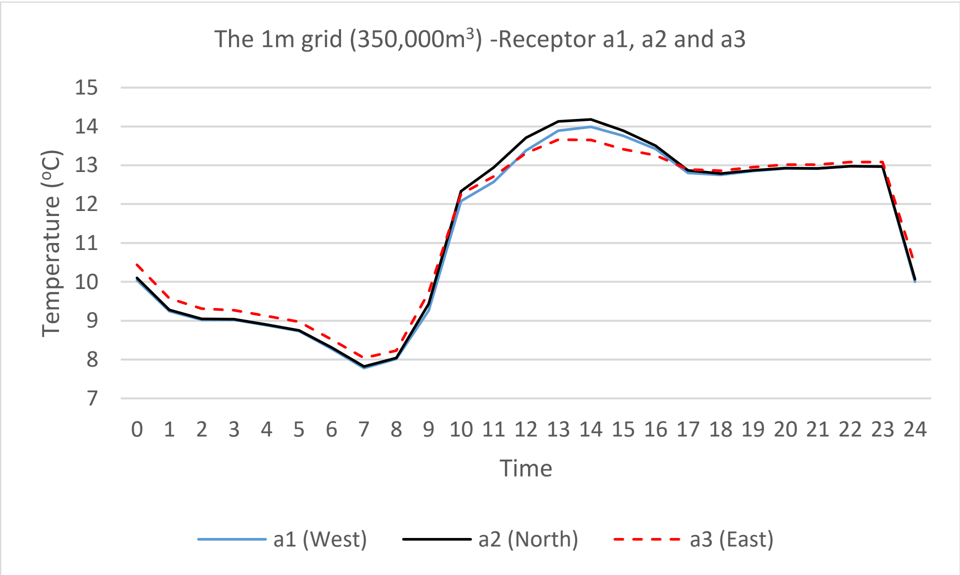


Diagram 7.28. Hourly air temperature receptor a1, a2 and a3 for the 1m grid (350,000m3)

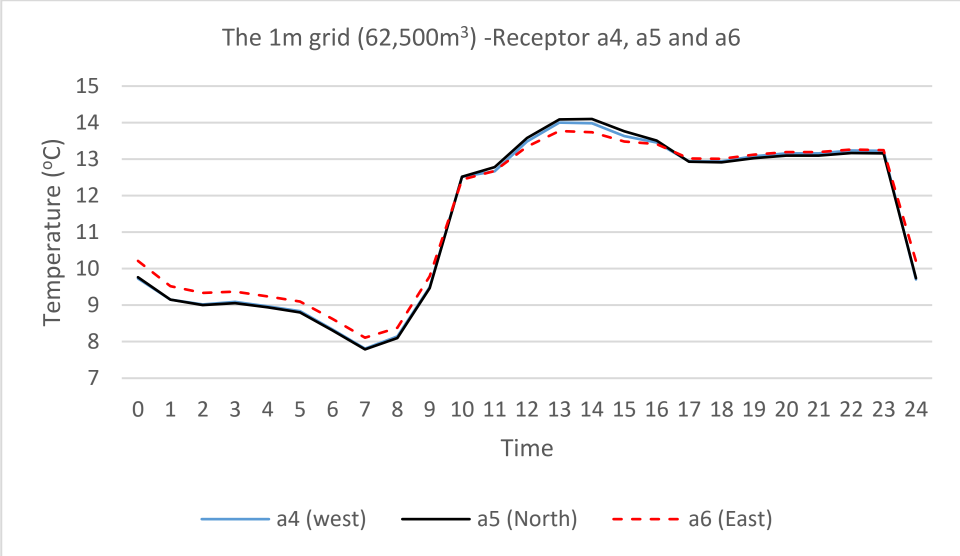


Diagram 7.29. Hourly air temperature receptor a4, a5 and a6 for the 1m grid (62,500m³)

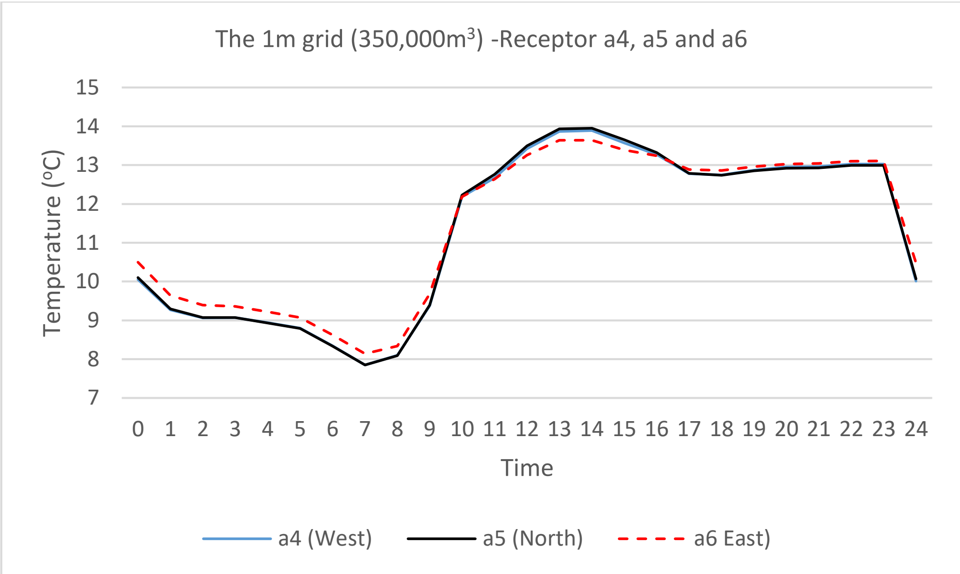


Diagram 7.30. Hourly air temperature receptor a4, a5 and a6 for the 1m grid (350,000m³)

The following five diagrams (7.31-7.35) show the data from the three different receptors in the 5m grid size model for five different sizes of domain area. In general, the three receptors have about the same value around midday (from 10a -3pm) for all site sizes with the largest gap no more than 0.1°C. This means the 5m grid model gets very small impact from the building shade and building facades as these receptors are farther from the building façade than the 1m grid receptors.

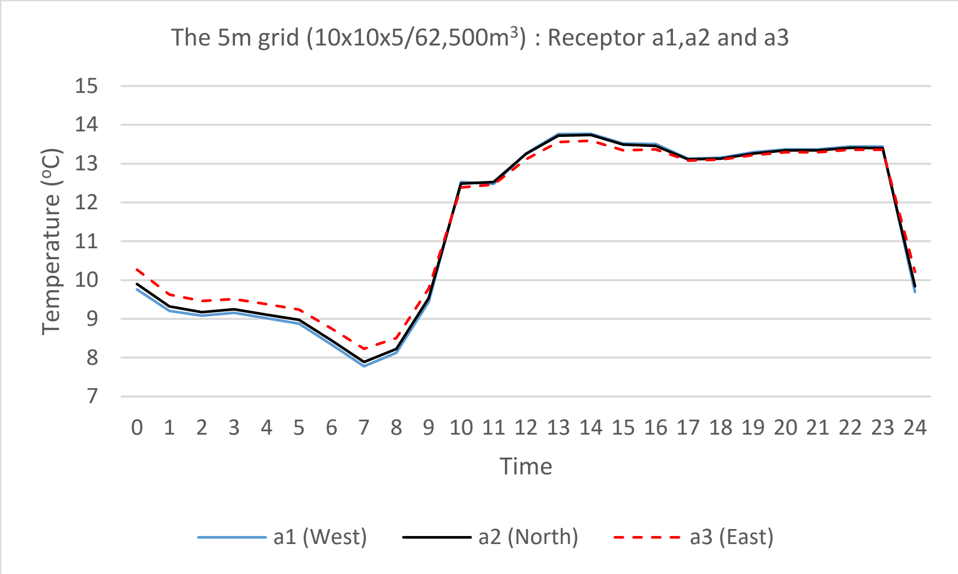


Diagram 7.31. Hourly air temperature receptor a1, a2 and a3 for the 5m grid (62,500m^3)

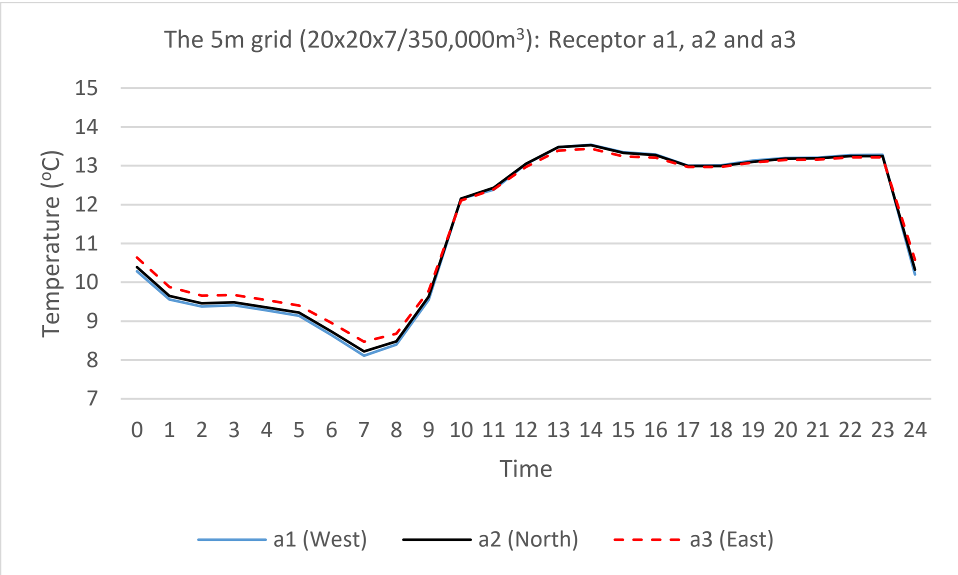


Diagram 7.32. Hourly air temperature receptor a1, a2 and a3 for the 5m grid (350,000m^3)

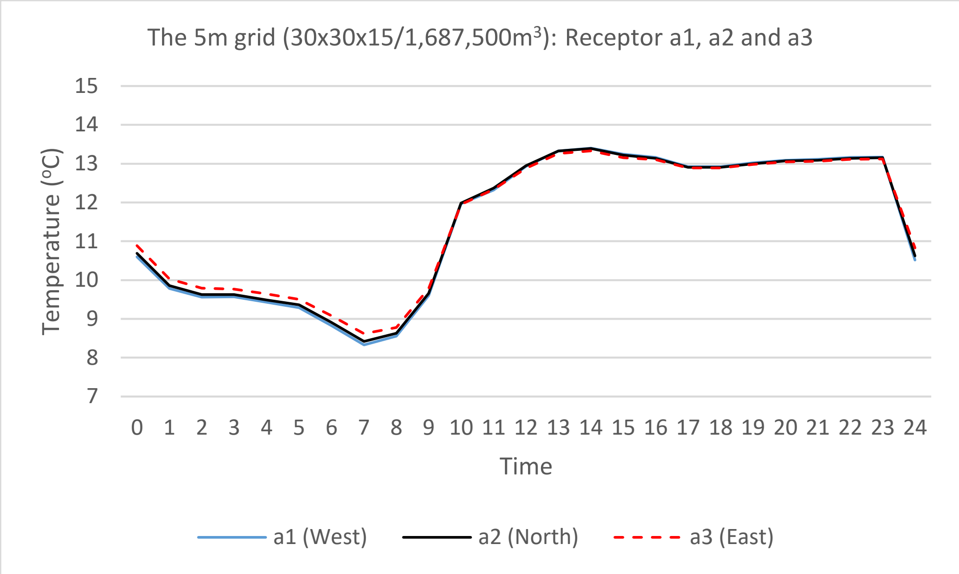


Diagram 7.33. Hourly air temperature receptor a1, a2 and a3 for the 5m grid (1,687,500m^3)

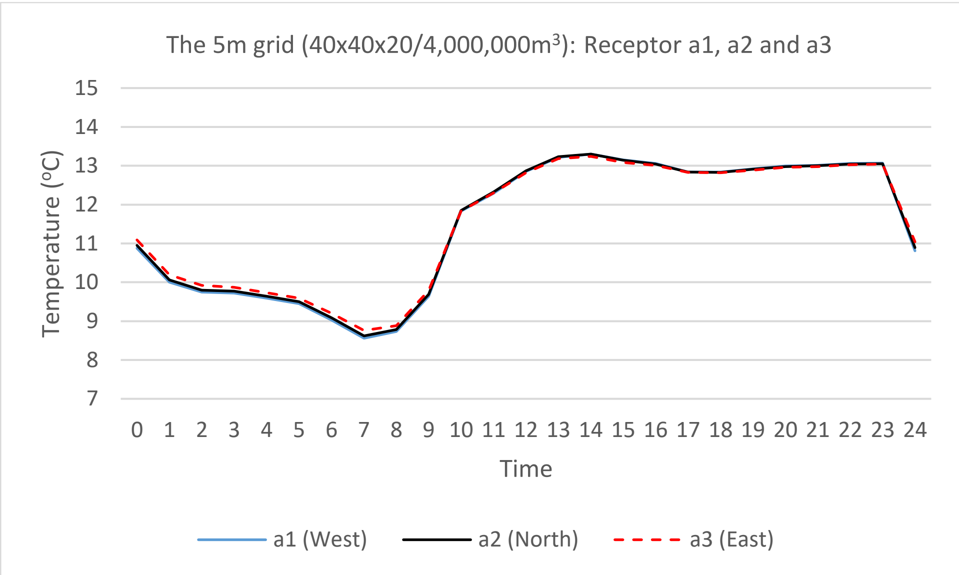


Diagram 7.34. Hourly air temperature receptor a1, a2 and a3 for the 5m grid (4,000,000m^3)

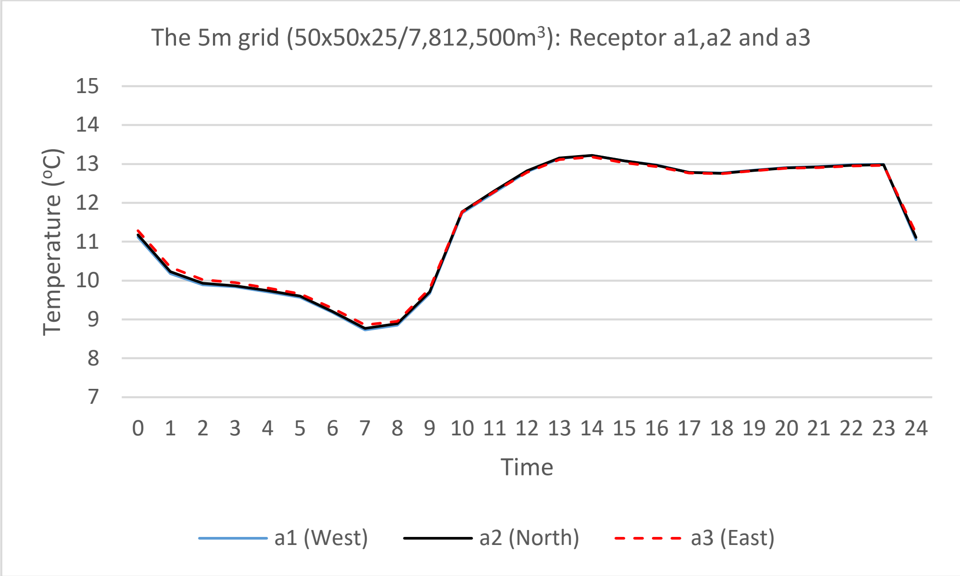


Diagram 7.35. Hourly air temperature receptor a1, a2 and a3 for the 5m grid (7,812,500m^3)

The difference between the three receptors for the 5m grid narrows with the increase of site size. There is a small difference for the 5m grid with the size of 62,500 m^3 (see Diagram 7.31) and 350,000 m^3 (see Diagram 7.32) averaging 0.3^{o}C from midnight to 8 am and 0.1^{o}C from midday to 3pm. Meanwhile, the largest site (7,812,500 m^3) produces the same trend in all three receptors but the biggest difference is under 0.1^{o}C (see Diagram 7.35).

For comparison, the results of receptors a4, a5 and a6 in the 1m grid of 62.500m^3 site size, also located 2.5m from building façade (see Diagram 7.29), have a difference by 0.3^{o}C on average from midnight to 8am and 0.2^{o}C from midday to 3pm. That trend is similar to that in the 5m grid of 62.500m^3 site size. That difference is considered insignificant for the energy simulation (discussed in Section 7.3.3), but it demonstrates more realistic simulated data. In this case, the building can block and absorb the solar radiation, before reducing and reheating the air temperature nearby. This can lead to the difference between three receptors (a1, a2 and a3) which are different in orientation. However, that difference is not demonstrated for the largest site (7,8125,000m^3).

7.3.4.3. Lessons and overall summary

There are some lessons from exploring the site size and receptor distance which are associated with the grid cell:

1. The bigger difference between the 1m and 5m grids (discussed in section 7.3.2.4) is because of the domain area which is associated with the grid-size change. Table 7.6 compares the temperature difference based on diagrams 7.15, 7.16 and 7,17. In general, the 5m grid size

with 7,812,500 m^3 has a significant difference toward the other three models by 1^{o}C on average from midnight to 8am, which can influence the simulation results in energy modelling by nearly 10% (discussed in section 7.3.3).

Grid Model	Site Size	Receptor	Distance (from façade)	Temperature difference		
				0am-8am	10am-3pm	5pm-11pm
West Direction (based on Diagram 7.15)						
The 1m	62,500 m^3	a1	0.5 m	Base	Base	Base
		a4	2.5 m	~0.0^{o}C	~0.1^{o}C	~0.0^{o}C
The 5m	62,500 m^3	a1	2.5 m	~0.0^{o}C	~0.2^{o}C	~0.2^{o}C
	7,812,500 m^3	a1	2.5 m	~1.0^{o}C	~0.8^{o}C	~0.2^{o}C
North Direction (based on Diagram 7.16)						
The 1m	62,500 m^3	a2	0.5 m	Base	Base	Base
		a5	2.5 m	~0.0^{o}C	~0.2^{o}C	~0.0^{o}C
The 5m	62,500 m^3	a2	2.5 m	~0.1^{o}C	~0.4^{o}C	~0.2^{o}C
	7,812,500 m^3	a2	2.5 m	~1.0^{o}C	~1.0^{o}C	~0.2^{o}C
North Direction (based on Diagram 7.17)						
The 1m	62,500 m^3	a3	0.5 m	Base	Base	Base
		a6	2.5 m	~0.1^{o}C	~0.0^{o}C	~0.0^{o}C
The 5m	62,500 m^3	a3	2.5 m	~0.1^{o}C	~0.1^{o}C	~0.1^{o}C
	7,812,500 m^3	a3	2.5 m	~0.9^{o}C	~0.6^{o}C	~0.3^{o}C

Table 7.6. Temperature difference between the 1m and 5m grid in 62,500m^3 as well as the 5m grid with 7,812,500 m^3

2. The increase of site size affects the simulated data, with the difference between the model with the normal (62,500m^3) and the largest site (7,812,500m^3) by averagely 0.9^{o}C in the west receptors (a1) from midnight to 8am. Such a difference can affect the energy simulation results by nearly 10% (discussed in 7.3.3). Moreover, the larger site leads to the higher temperature from midnight to 8am and lower temperature from 10 am to 11 pm. The two following tables summarise the temperature difference in different site sizes for the 1m and 5m grid.

Receptor	Distance from facade	Temperature difference of 62,500m^3 compared to 350,000 m^3	
		0 am to 8 am	10 am to 11pm
a1	0.5m	~0.0^{o}C	~0.2^{o}C
a2	0.5m	~0.0^{o}C	~0.2^{o}C

a3	0.5m	~0.0ºC	~0.2ºC
a4	2.5m	~0.0ºC	~0.2ºC
a5	2.5m	~0.0ºC	~0.2ºC
a6	2.5m	~0.0ºC	~0.2ºC

Table 7.7. Temperature difference in the different site size for the 1m grid

Receptor	Temperature difference of 62,500m³ compared to larger site size							
	Site size (m³) from 0 am to 8 am				Site size (m³) from 10 am to 11 pm			
	350,000	1,687,500	4,000,000	7,812,500	350,000	1,687,500	4,000,000	7,812,500
a1 (West)	~0.3ºC	~0.5ºC	~0.7ºC	~0.9ºC	~0.2ºC	~0.3ºC	~0.4ºC	~0.5ºC
a2 (North)	~0.3ºC	~0.5ºC	~0.7ºC	~0.8ºC	~0.2ºC	~0.3ºC	~0.4ºC	~0.4ºC
a3 (East)	~0.2ºC	~0.3ºC	~0.5ºC	~0.6ºC	~0.1ºC	~0.2ºC	~0.3ºC	~0.4ºC

Table 7.8. Temperature difference in the different site size for the 5m grid

3. The increase of site size as well as grid cell might lead to unrealistic results as it does not demonstrate the effect of building shade and façade in the simulated data. In this case, the solar radiation which is blocked and absorbed by building facades can reduce or increase the air temperature at particular time. However, the larger domain area in the 5m grid (350,000-7,812,500 m^3) does not produce the results which demonstrated these effects since all three receptors comparatively have the same daytime hourly temperature. Only the model of 1m grid with 62,500m^3 grid demonstrates obvious difference from midday to 3 pm with the biggest difference by averagely 0.5ºC. Such a difference might be not significant for the energy simulation (discussed in Section 7.3.3), but it demonstrates that the 1m grid with 62.500m^3 produces data which is more affected by building shade and façade.

Grid Model	Site Size	Receptor	Distance (from façade)	Temperature Difference (12pm-3pm)
The 1m	62,500 m³	a1 (West)	0.5 m	~0.2ºC
		a2 (North)		~0.5ºC
		a3 (East)		Base
	350,000 m³	a1 (West)	0.5 m	~0.2ºC
		a2 (North)		~0.5ºC
		a3 (East)		Base
	62,500 m³	a4 (West)	2.5 m	~0.2ºC
		a5 (North)		~0.2ºC
		a6 (East)		Base

	350,000 m^3	a4 (West)	2.5 m	~0.2^{o}C
		a5 (North)		~0.2^{o}C
		a6 (East)		Base
The 5m	62,500 m^3	a1 (West)	2.5 m	~0.1^{o}C
		a2 (North)		~0.1^{o}C
		a3 (East)		Base
	350,000 to 7,8125,000 m^3	a1 (West)	2.5 m	~0.0^{o}C
		a2 (North)		~0.0^{o}C
		a3 (East)		Base

Table 7.9. Temperature difference between three different receptors for the 1m and 5m grid in different site sizes

4. The computational time in ENVI-met model is strongly related to the grid-cell number instead of the domain area (see Table 7.5). The less number of grid cells, the faster computational time.

7.3.5. Simulation duration: Is 72-hours simulation duration necessary?

This section follows up one of the key questions which was discussed in section 7.1.2 to see the difference of simulation results for each day within 72 hours simulation duration. The comparison for each day simulation results is made based on the model with the 1m grid with 0.8ms^{-1} as well as the 5m grid with 0.8ms^{-1} and 12ms^{-1}, which were simulated in section 7.3.2. This aims to see how different the results are with variation of grid size and wind speed.

7.3.5.1. Comparison and analysis

The Diagram 7.36-7.38 compares the results of each day in the three receptors for the 1m grid (0.8m^{s-1} of wind speed). Overall, the results of the second and third day are the same, with the difference no more than 0.1^{o}C. Meanwhile, there is an average difference of 0.6^{o}C from 2 to 8 am. The biggest difference is at 2am of 1^{o}C. Thus, the results of the first day can lead to the difference by 5-7% (discussed in section 7.3.3) in energy simulation compared to the second and third day.

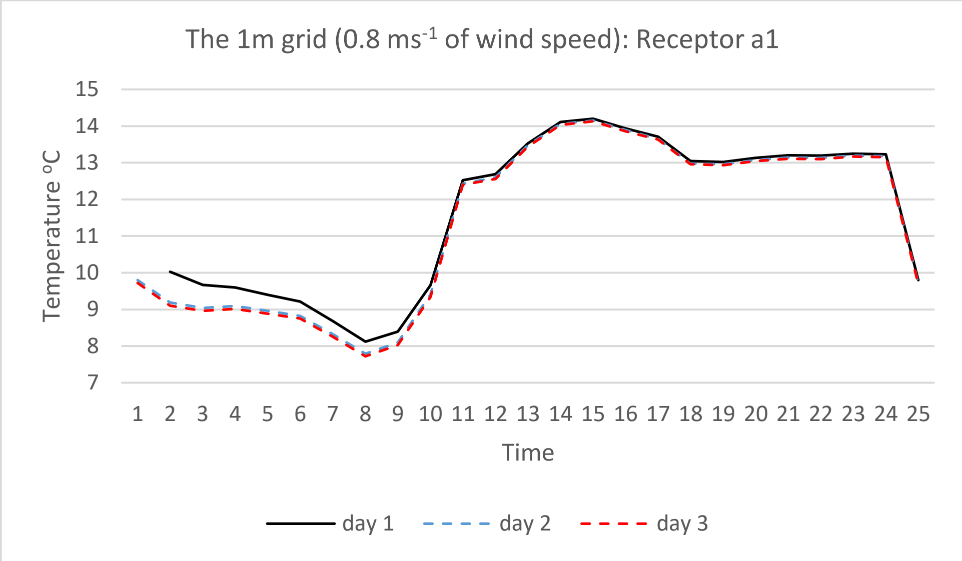


Diagram 7.36. Hourly air temperature of the 1m grid model (wind speed: 0.8ms^{-1}) from receptor a1 for 3 days iteration

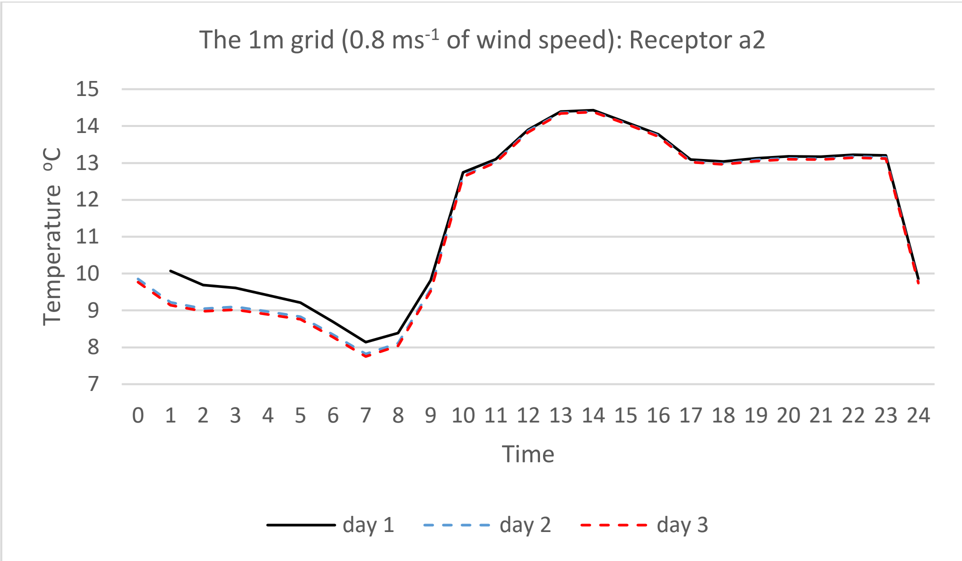


Diagram 7.37. Hourly air temperature of the 1m grid model (wind speed: 0.8ms^{-1}) from receptor a2 for 3 days iteration

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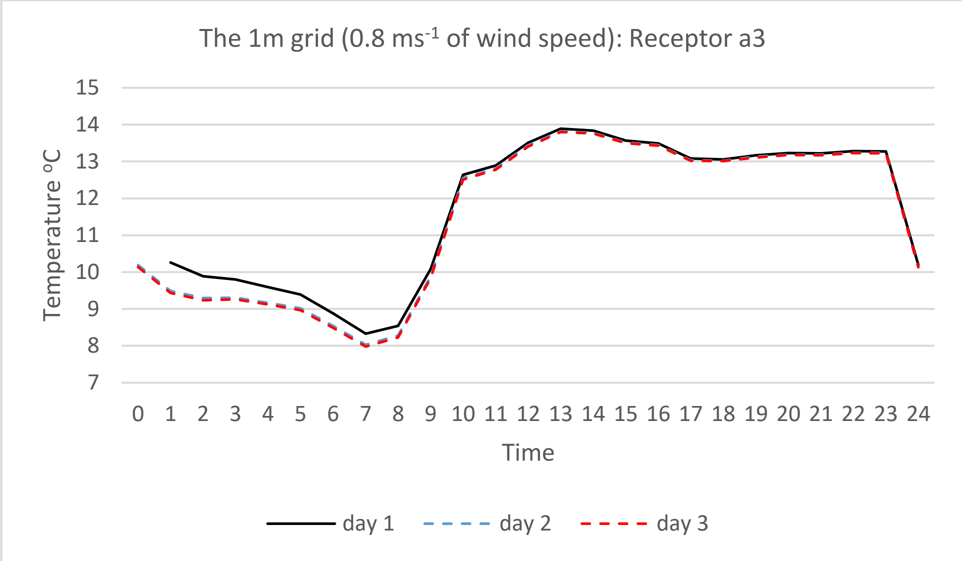


Diagram 7.38. Hourly air temperature of the 1m grid model (wind speed: 0.8ms^{-1}) from receptor a3 for 3 days iteration

For the 0.8ms^{-1} wind speed, the 5m grid has the same trend of temperature difference as the 1m grid, as shown in Diagram 7.39-7.41. The results of the second and third day are similar while the temperature difference compared to the first day by averages 0.6°C warmer from 2 to 8 am.

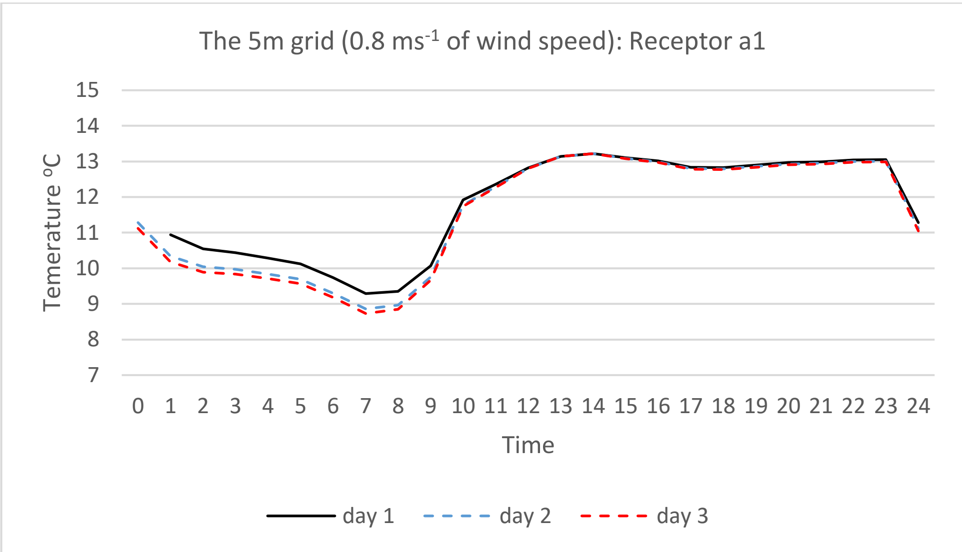


Diagram 7.39. Hourly air temperature of the 5m grid model (wind speed: 0.8ms^{-1}) from receptor a1 for 3 days iteration

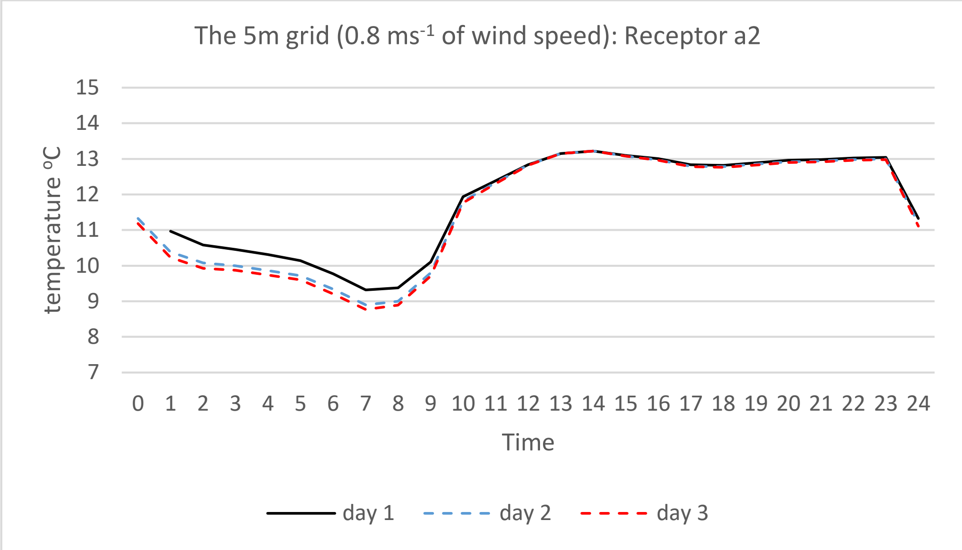


Diagram 7.40. Hourly air temperature of the 5m grid model (wind speed: 0.8ms^{-1}) from receptor a2 for 3 days iteration

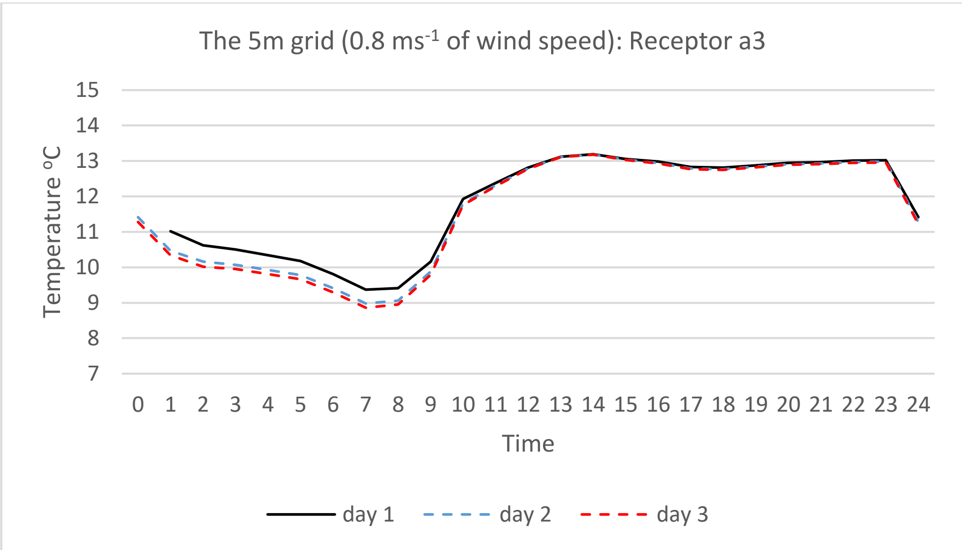


Diagram 7.41. Hourly air temperature of the 5m grid model (wind speed: 0.8ms^{-1}) from receptor a3 for 3 days iteration

Diagram 7.42-7.44 show the simulated data for the 5m grid size with 12ms^{-1} of wind speed. In general, the simulation results are relatively the same for each day with the difference no more than 0.1°C. The output in the first day has a gap in the data series where one hourly data (at 12.00) is not produced (unexplainable behaviour of ENVI-met simulation).

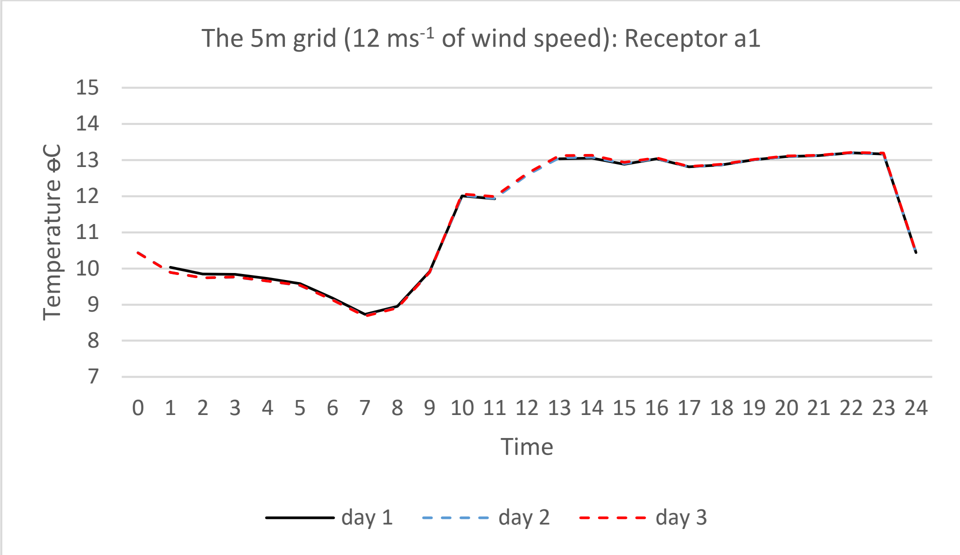


Diagram 7.42. Hourly air temperature of the 5m grid model (wind speed: 12ms^{-1}) from receptor a1 for 3 days iteration

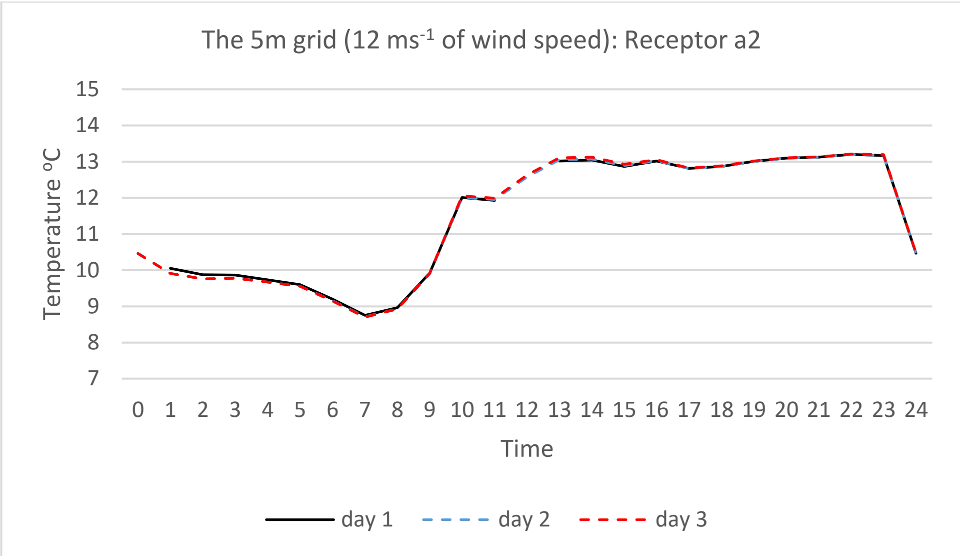


Diagram 7.43. Hourly air temperature of the 5m grid model (wind speed: 12ms^{-1}) from receptor a2 for 3 days iteration

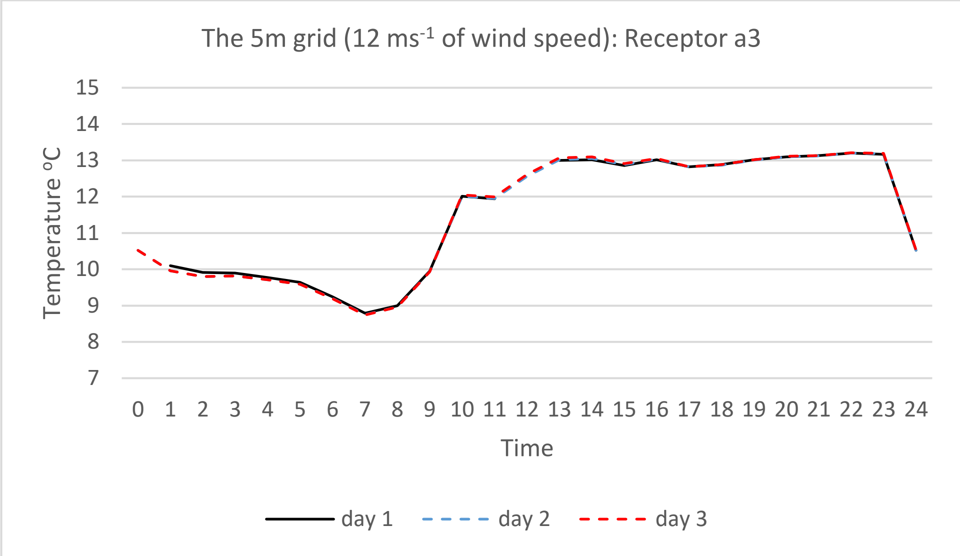


Diagram 7.44. Hourly air temperature of the 5m grid model (wind speed: 12ms^{-1}) from receptor a3 for 3 days iteration

The trend of air temperature difference between the 1 and 5m grid with 0.8ms^{-1} is the same. Those models produce the consistent result after the first 8 hours. Meanwhile, the 5m grid with 12ms^{-1} produces similar results each day, but one hourly data (at 12.00) is not produced on the first day. The model with 0.8ms^{-1} of wind speed takes between six and eight hours for stability to produce consistent results. This suggests that the simulation duration can be set much shorter. In this case, the simulation duration could be set 30 hours instead of 72 hours.

7.3.5.2. Testing 30-hours simulation duration

This section tests whether the 30-hour simulation (see section 7.3.5.1). will produce the similar results to the 72-hour simulation. This test uses the 1m grid with 0.8ms^{-1} wind speed. The simulation period starts at 6 pm on 19th June, lasting until midnight on 20th June, gathering 24 hours' simulated data for 20th June for analysis.

Diagram 7.45-7.47 compares the 30-hour with the 72-hour simulation for the three receptors (a1, a2 and a3). Overall, both models produce similar hourly air temperature for the 20th June, with the average difference of 0.2°C from midnight to 8am. Such a difference is considered insignificant as it can affect by less than 3% of simulation results in energy modelling (discussed in section 7.3.3).

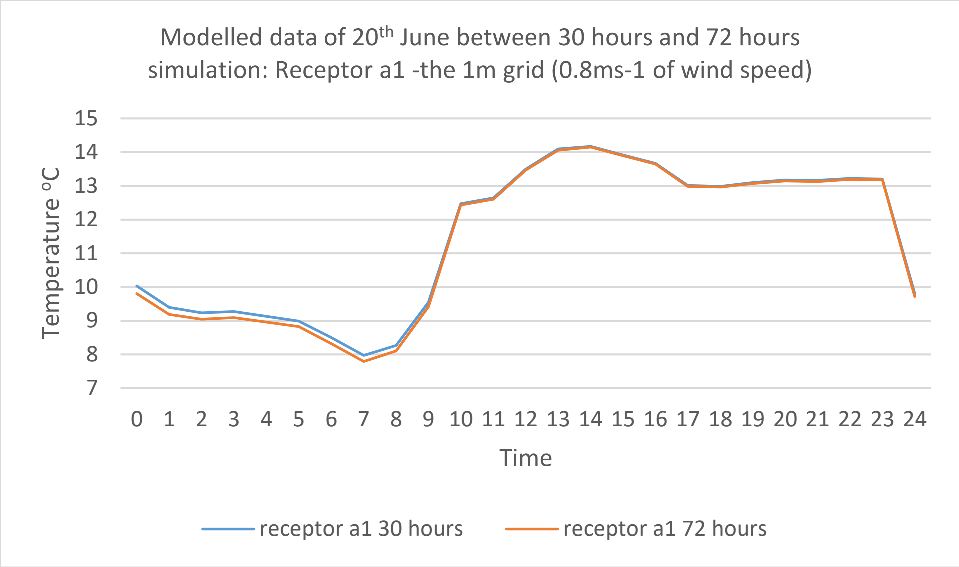


Diagram 7.45. Simulated data between 30- and 72- hours simulation duration for the simple model in the receptor a1

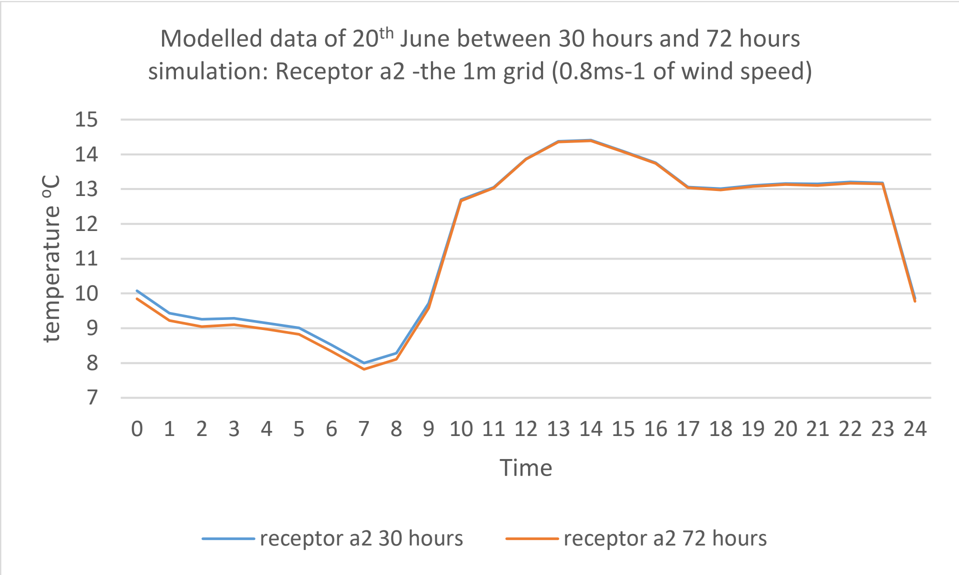


Diagram 7.46. Simulated data between 30- and 72- hours simulation duration for the simple model in the receptor a2

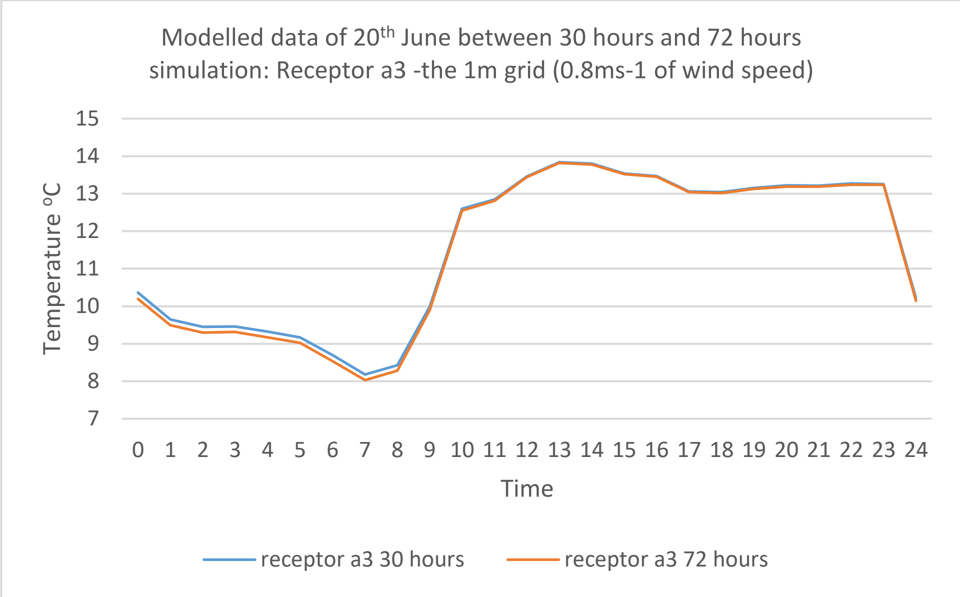


Diagram 7.47. Simulated data between 30- and 72- hours simulation duration for the simple model in the receptor a3

Table 7.10 shows the computational time for the 30-hours simulation is 2.3 times faster than the 72-hours.

Simulation period	The simple model (the 1m grid of 0.8ms-1 of wind speed)
30 hours	6h 45 min
72 hours	15h 49min

Table 7.10. The computational time between the 30- and 72- hours simulation period

As the 30-hour simulation produces a similar quality to the 72-hour simulation, but with much faster computational time, it is preferable.

7.3.6. Parametric study for wind speed and direction

This section investigates whether the wind input influences the simulated data of air temperature. In this test, the value of wind speed and direction input were changed and the results from each receptor compared.

7.3.6.1. Input and process

This test develops the 5m grid model with 50x50x25 of domain area as this model successfully ran high wind speeds without any technical error (see section 7.3.2.1 and Table 7.1). The model previously applied 12ms^{-1} of wind speed with 245^{o} of direction (based on 24 hours average data on 20th June). In this parametric test, the wind speed value is firstly reduced and then increased by 50% to see how much the wind speed modifies the ENVI-met microclimate. The simulation results of the 5m grid with 0.8ms^{-1} of wind speed from the section 7.3.2 (Diagram 7.7, 7.8, and

7.9) are also compared. Table 7.11 shows the computational time for the 5m grid-size model with different wind speed. Overall, higher wind speed led to longer computational time.

Name	Wind Speed (m/s)	Process and Computational Time
Low Wind Speed	0.8	Success -14h 45min
Annual Min daily	6	Success -15h 8 min
Second Trial	12	Success -16h 10min
Annual Average daily	18	Success -17h 19min

Table 7.11. Simulation Process of Wind Speed Test

For testing the impact of wind direction, there are two models tested: the 1m grid-size for low wind speed ($0.8ms^{-1}$) and the 5m grid-size for high wind speed ($12ms^{-1}$). Both models are modelled in 50x50x25 of grid cells. This aims to see whether the wind direction influences the results in relation to the wind speed. There are three different scenarios for wind-speed testing:

1. North Direction (0^o). All receptors are in the windward position. The receptor a1 and a3 experiences similar wind condition.
2. West Direction (270^o). Receptor a1 and a2 are in windward position while a3 is in the leeward position.
3. North East Direction (315^o). Receptor a1 and a2 are in the windward position while the a3 is in the leeward position.

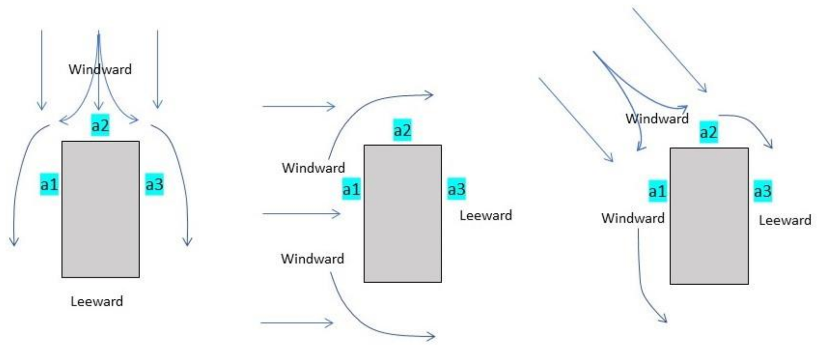


Figure 7.4. Three scenarios for wind-direction tests: North -0^o (Left), West -270^o (Middle), North-East -315^oC (Right)

There are four different results which are compared including the prevailing wind direction of 245^o (south-west direction), which was simulated previously in the grid-size test.

7.3.6.2. Results

The three diagrams (7.48-7.50) below compare hourly air temperature produced by the grid size of 5m in the different wind speed condition. In general, the four models with different wind speed produce similar results, with the average difference no more than 0.1^oC.

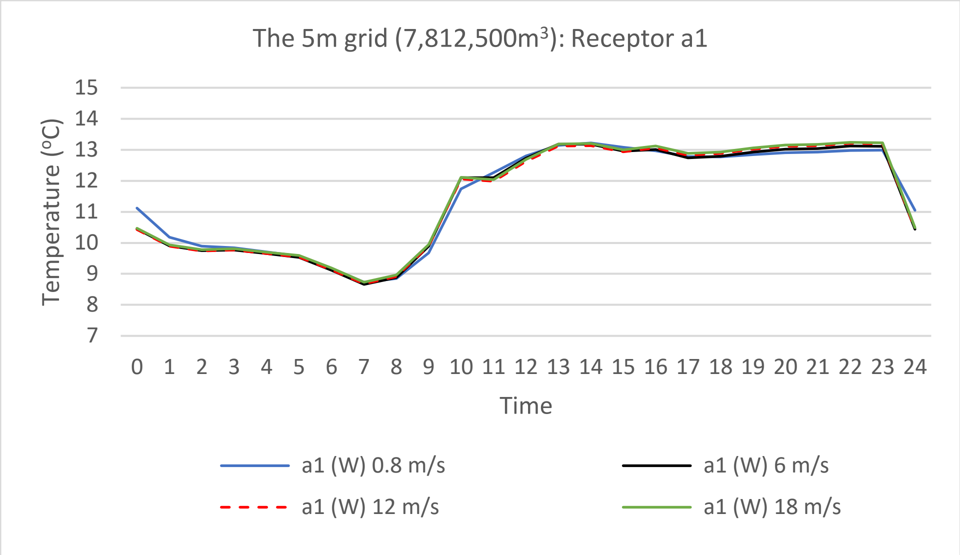


Diagram 7.48. Hourly air temperature receptor a1 (west) for different wind speed scenarios

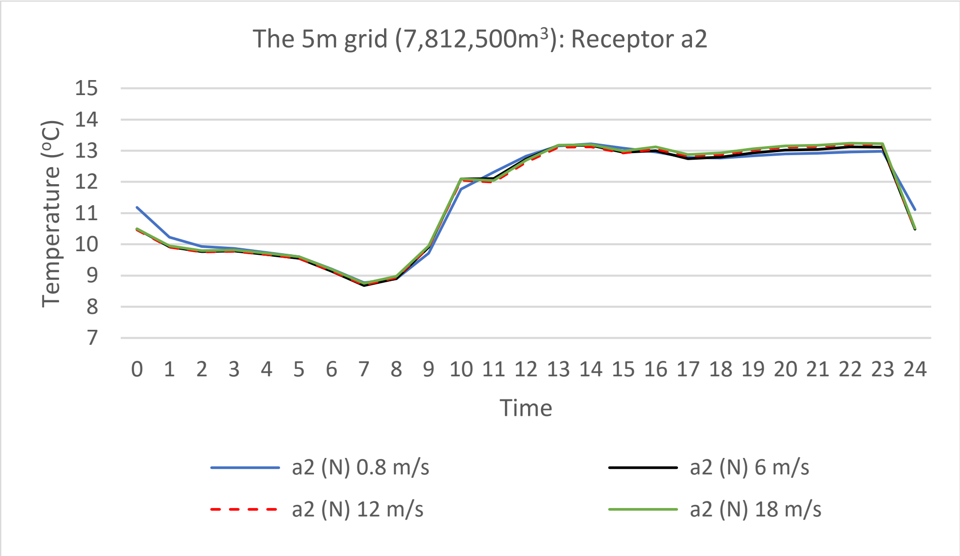


Diagram 7.49. Hourly air temperature receptor a2 (north) for different wind speed scenarios

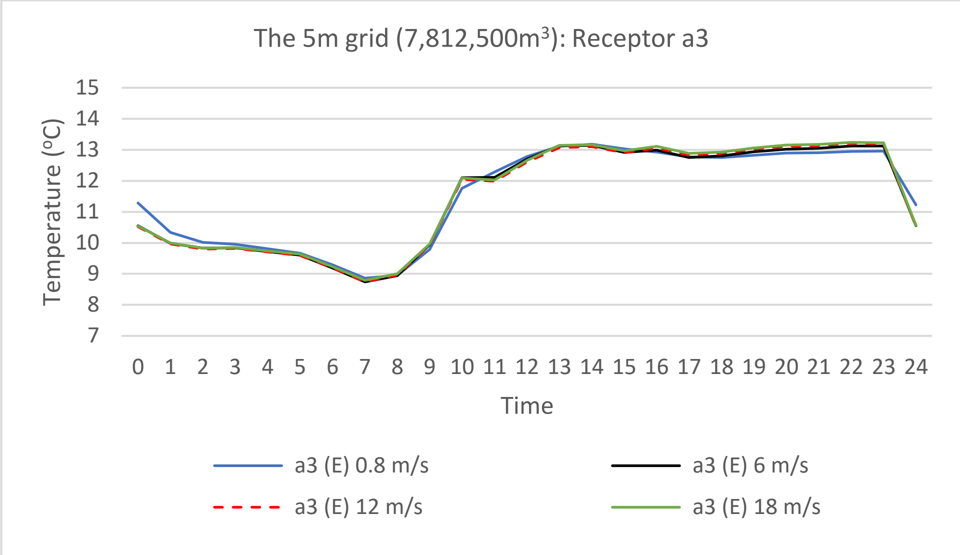


Diagram 7.50. Hourly air temperature receptor a3 (East) for different wind speed scenarios

The three following diagrams compares the simulated data for the 1m grid with 0.8ms^{-1} in the different wind direction. Overall, all scenarios of wind direction produce the same results. Both the West and North receptors (a1 and a2) have no difference more than 0.1°C in average. Meanwhile, (a3) there is a tiny difference of averaging 0.1°C in the east receptor.

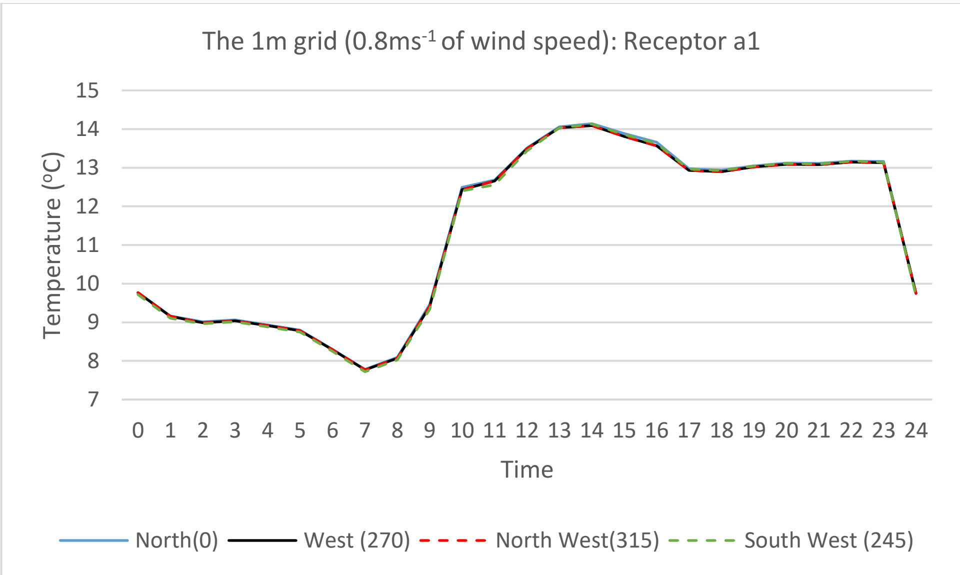


Diagram 7.51. Hourly air temperature receptor a1 for different wind direction in the 1m grid size (wind speed: 0.8ms^{-1})

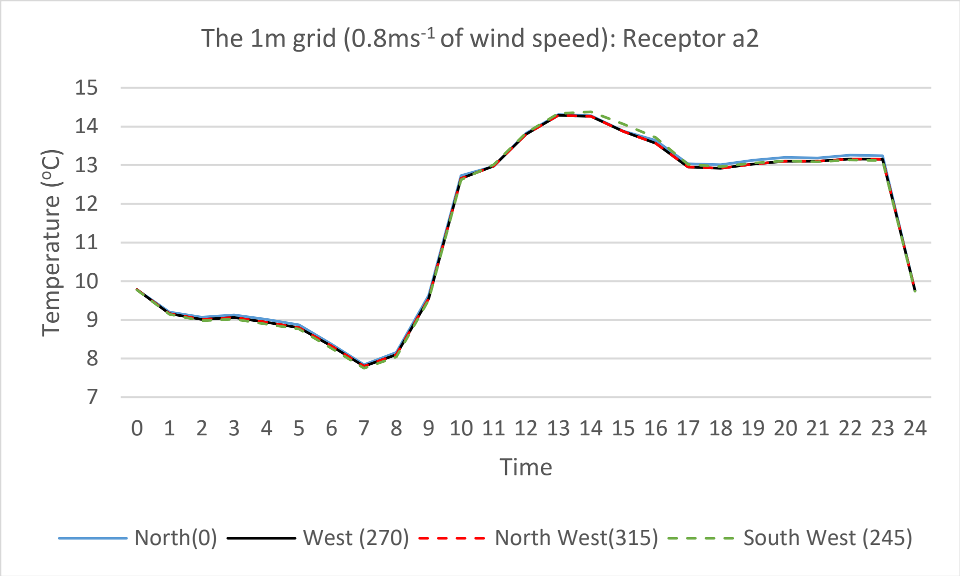


Diagram 7.52. Hourly air temperature receptor a2 for different wind direction in the 1m grid size (wind speed: 0.8ms^{-1})

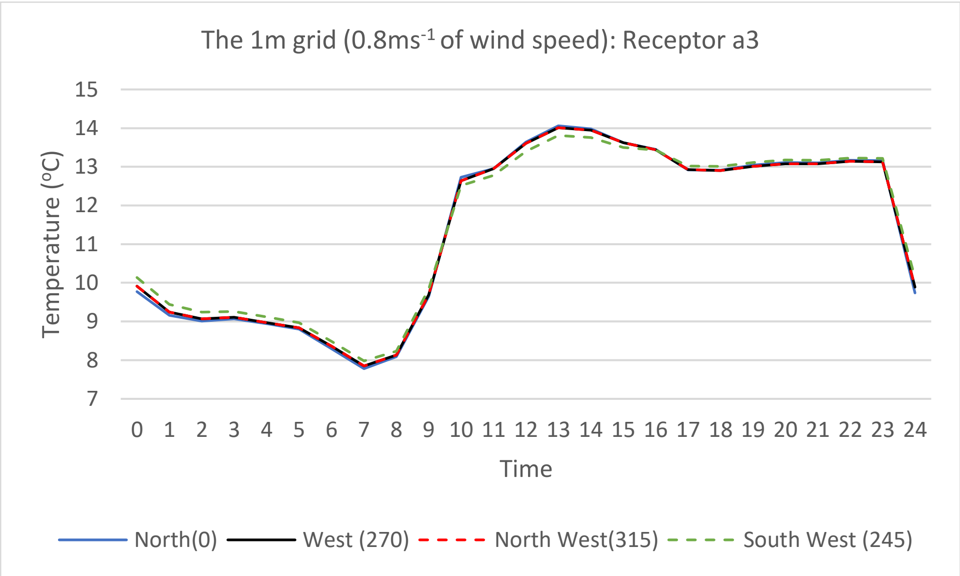


Diagram 7.53. Hourly air temperature receptor a3 for different wind direction in the 1m grid size (wind speed: 0.8ms^{-1})

The 5m grid size with 12ms^{-1} of wind speed also produces the same simulated data in the four wind-direction scenarios in which there is no difference by no more than 0.1°C.

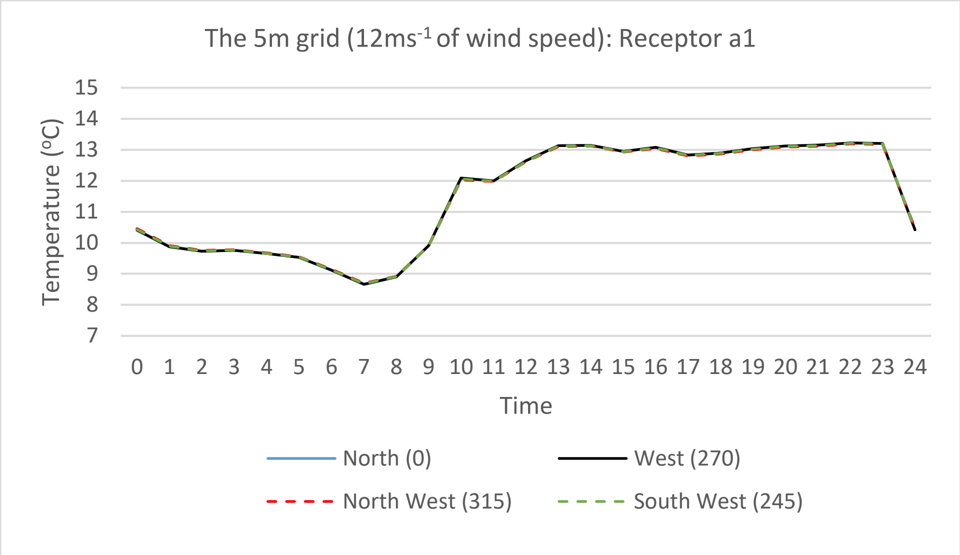


Diagram 7.54. Hourly air temperature receptor a1 for different wind direction in the 5m grid (wind speed: 12ms^{-1})

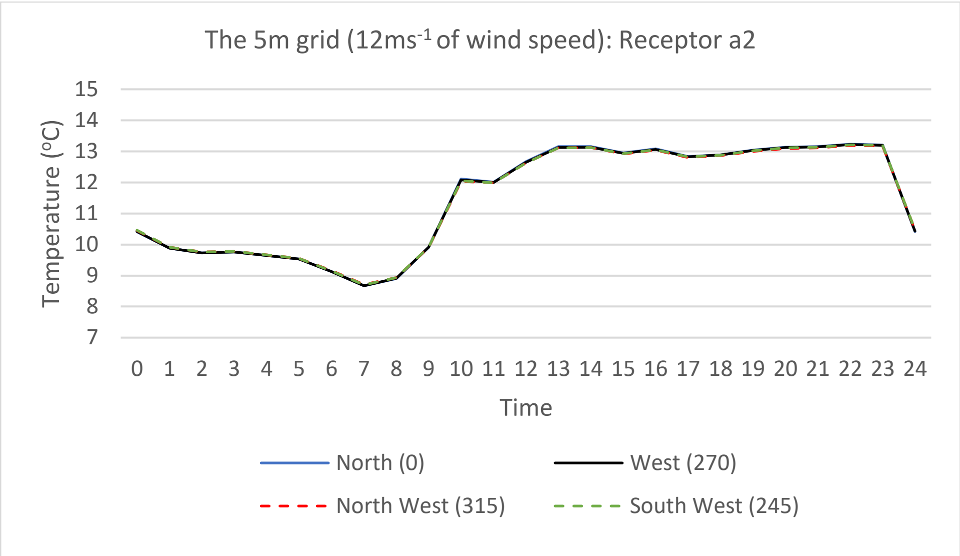


Diagram 7.55. Hourly air temperature receptor a2 for different wind direction in the 5m grid (wind speed: 12ms^{-1})

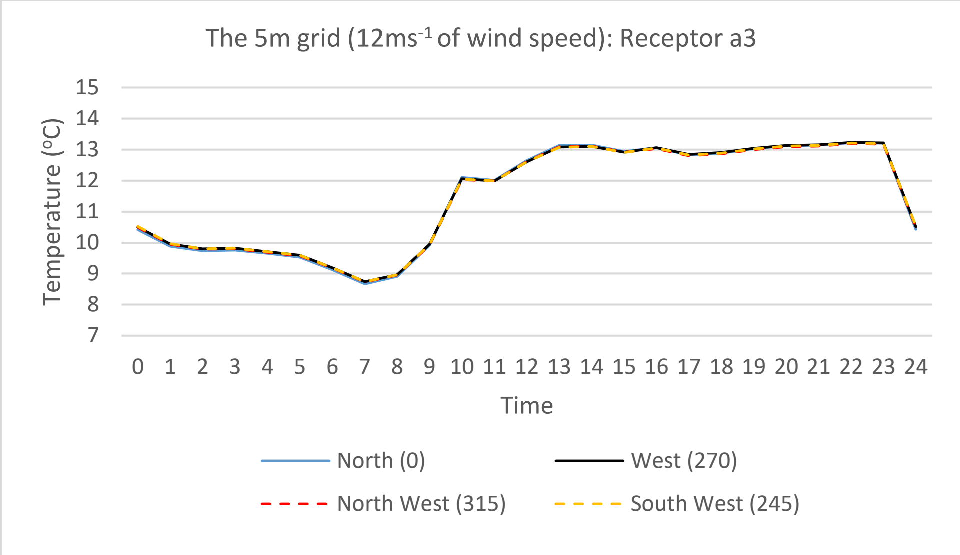


Diagram 7.56. Hourly air temperature receptor a3 for different wind direction in the 5m grid (wind speed: 12ms^{-1})

The results from the wind speed and direction tests show that, in general, wind has no influence on the simulated data in ENVI-met model.

7.3.6.3. Additional tests for roughness value

Besides wind speed and direction input, there is also roughness input in the meteorological basic setting. In ENVI-met, there are only three types of roughness value, which are: 0.1, 0.01 and 0.001. However, there is no guidance or explanation found in the technical documentation on ENVI-met website about the relation between these values and site-surface type. This input defines the surface roughness on the site. A study by Salata, et al. (2016) relates these values with the typical values of roughness lenghth proposed by Stull (1988) when inputting basic parameters in ENVI-met model.

Soil Covering	Typical Z_o Value
Urban Areas	0.5-2.0 m
Suburban Areas	0.3-0.5 m
Forests	0.5-1 m
Farmlands	2-10 cm
Grasslands	0.5-5 cm
Rough Sea	1 mm
Calm Sea	0.1 mm

Table 7.12. Typical Values of the aerodynamic roughness length (Stull, 1988)

The table above (Stull, 1988) shows typical value for the aerodynamic roughness length (Z_o). Based on that table, the roughness 0.1 in ENVI-met can generally represent the suburban area and farmland (nearly 0.1), while 0.01 and 0.001 generally describes the roughness for the grasslands and coastal area (sea) respectively. The default setting for all cases examined was set by 0.01. This tests the 1m grid (0.8ms^{-1} of wind speed) and the 5m grid (12ms^{-1} of wind speed) with the variation of roughness values to investigate how much they influence the simulated air temperature in ENVI-met.

The six following diagrams compares the results from the 1m grid (0.8ms^{-1} of wind speed) and 5m grid (12ms^{-1} of wind speed) in the different roughness value. All diagrams show that all models with different roughness value produce the same simulated air temperature – the difference is no more than 0.1°C.

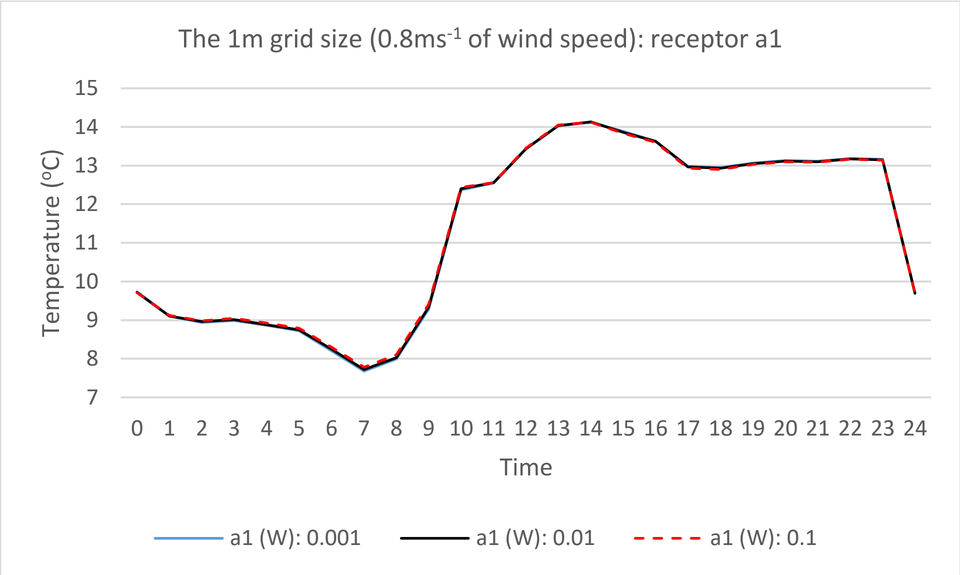


Diagram 7.57. Hourly air temperature receptor a1 in the 1m grid size for different roughness values

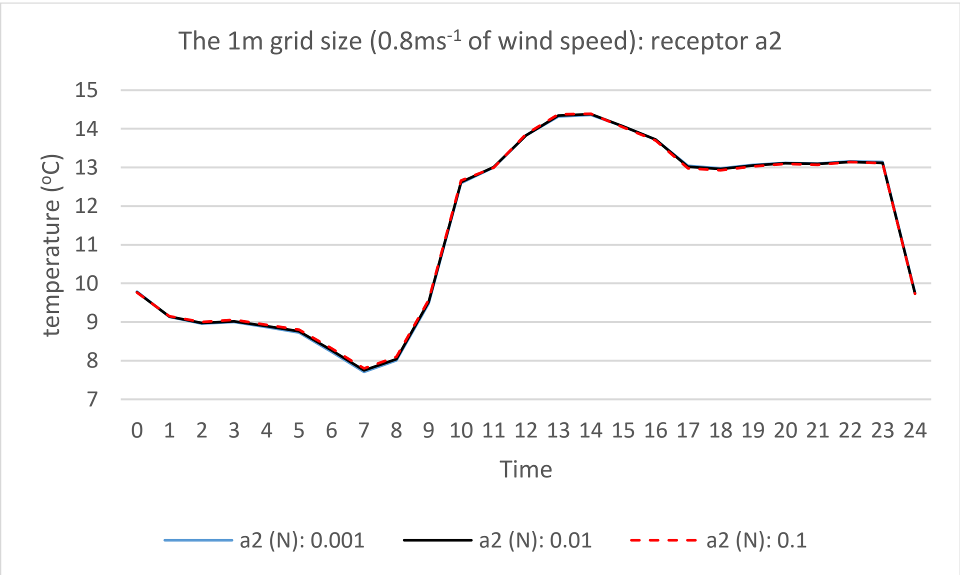


Diagram 7.58. Hourly air temperature receptor a2 in the 1m grid size for different roughness values

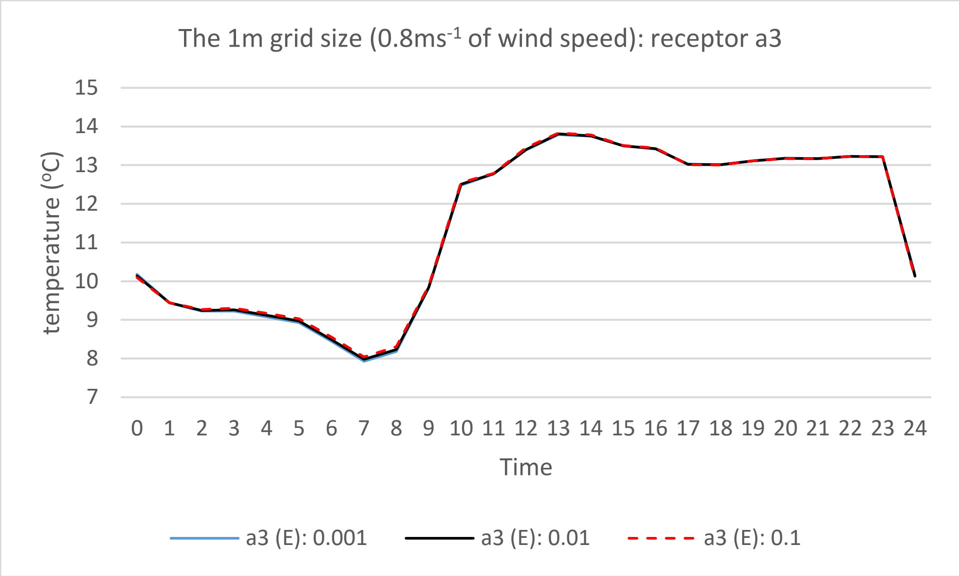


Diagram 7.59. Hourly air temperature receptor a3 in the 1m grid size for different roughness values

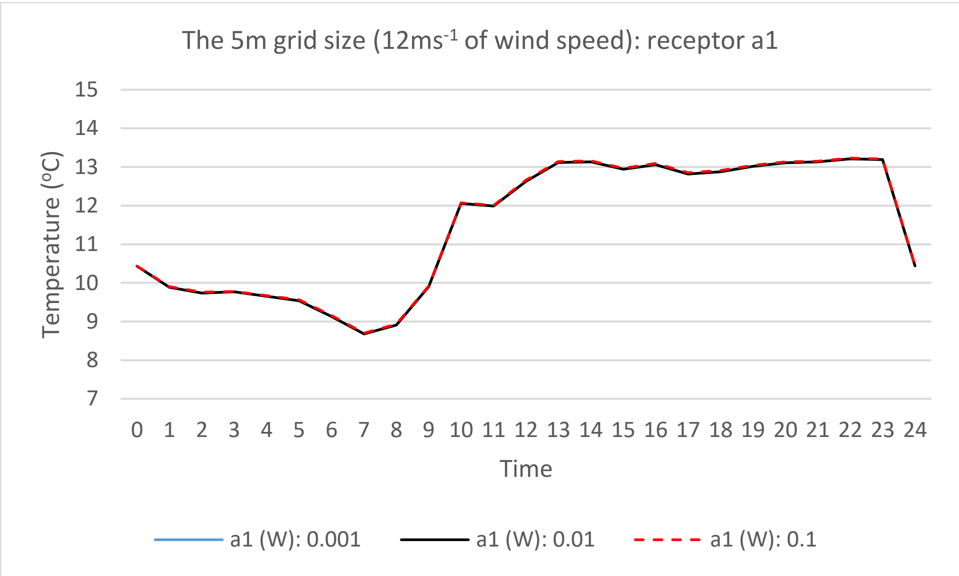


Diagram 7.60. Hourly air temperature receptor a1 in the 5m grid size for different roughness values

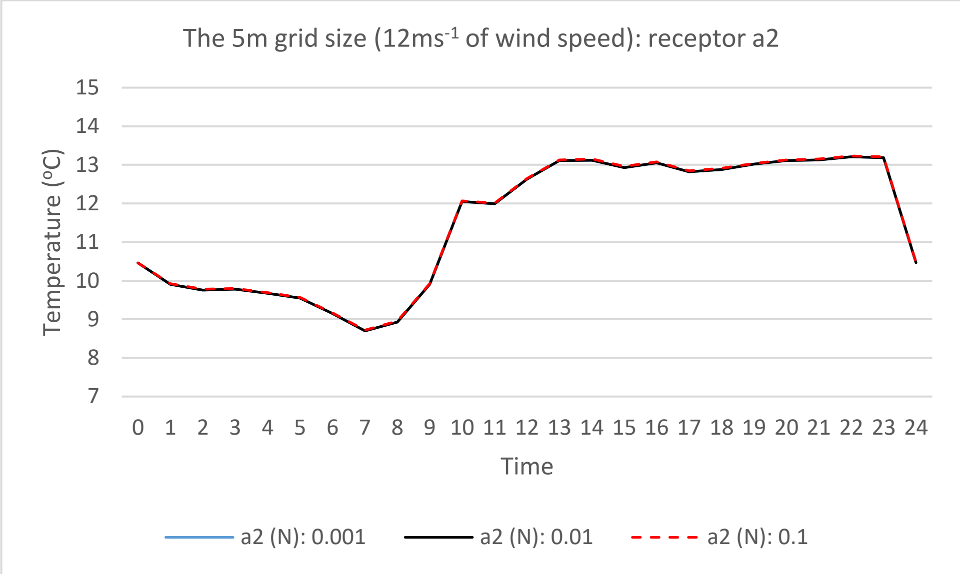


Diagram 7.61. Hourly air temperature receptor a2 in the 5m grid size for different roughness values

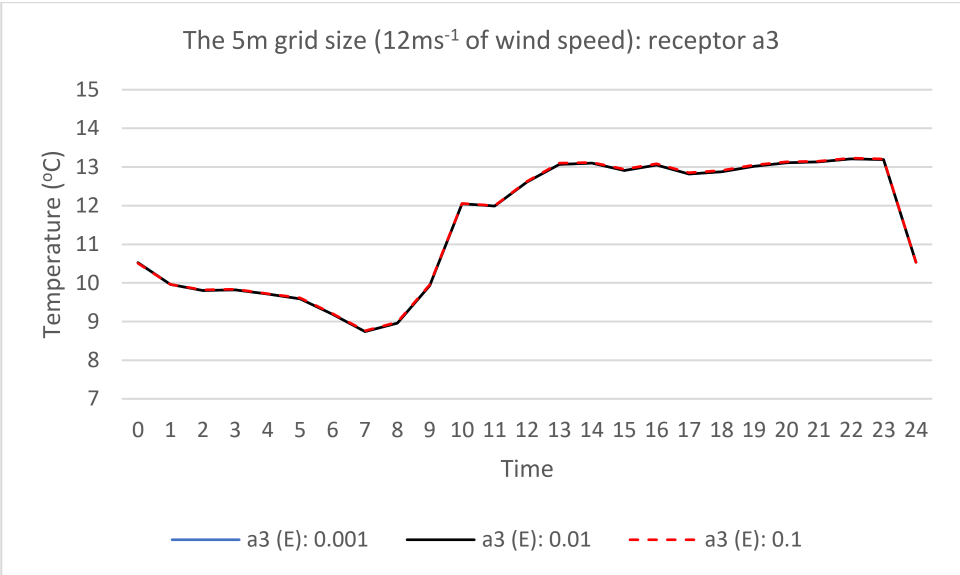


Diagram 7.62. Hourly air temperature receptor a3 in the 5m grid size for different roughness values

7.3.6.4. Lessons and discussions

From comparing the results from the tests for wind input (wind speed and direction, and roughness value), it is concluded that wind input in ENVI-met do not have any influence on simulated air temperature. In this case, the change of wind speed and direction as well as roughness value does not lead to the air temperature difference by no more than 0.1°C for both the 1m and 5m grid. This indicates that wind system in ENVI-met model does not heat or cool the atmosphere. This means that none of the wind input in the basic meteorological setting is important in influencing air temperature and RH in ENVI-met model. This finding was also stated by the previous research by (Middel, Hab, Brazel, Martin, & Guhathakurta (2014).

7.3.7. Conclusion and suggestion

From conducting a parametric study for the basic input in ENVI-met, it is concluded that:

1. The model with 1m grid-size in 62,500m^3 (50x50x25 cells) of site size is preferable for further modelling in investigating the impact of site parameters. First, it has the finest resolution and allow creating desirable house model and site objects within the range of 1-10 meters such as trees, nearby buildings and slopes. Based on the section 7.3.4.3, the 1m grid-size in 62,500m^3 produces more realistic results compared to other grid-size. In this case, it demonstrates difference of air temperature data during the daytime, which is related to the effect of building shade and surface heating. Also, this model allows the receptor to be placed as close as possible to the building facades, which represent the microclimate interacting to the building.
2. The 30 hours of simulation duration is preferable as it produces the similar quality to the 72 hours but with much faster computational time (discussed section 7.3.5.2).
3. The wind input in ENVI-met (wind speed and direction, and roughness value) is not important factor in affecting the simulated air temperature. Thus, for the further modelling, the wind speed can be purposely set by 0.8ms^{-1} to avoid technical error during initialization in simulation, (see section 7.3.2.1). The roughness input value can follow the default setting by 0.1.

However, the parametric study, (section 7.3) used the simple house model with the flat-open surroundings. It is still unknown whether the selection of the 1m grid-size with 62,500m^3 can produce reliable results. Therefore, a model evaluation with the 1m grid-size model is discussed in the next section (7.4).

7.4. Model evaluation (Validation)

Since ENVI-met is a physical model, the quality of simulation results depends on the accuracy of input data (ENVI_MET, 2018c). Analysis from Section 7.3 found that some basic input parameters have no large influence on simulated data in ENVI-met e.g. wind input. However, it is still unknown how much those parameters alter input meteorological data, especially site object properties such as soil condition. The difference of object properties between the model and reality can lead to the discrepancies between simulation results and measured data. For example, the "Loamy soil" provided by ENVI-met database may not match Loamy Soil on the real site, and the albedo and water content of soil might in the model be very different from the reality.

Therefore, it is important to evaluate the ENVI-met model by comparing the real data and simulated data.

In this section, one model was created based on the surroundings and microclimate condition of one weather station in Wellington (Kelburn). In this case, the model inputs microclimate data based on the observed data produced by Kelburn weather station. Then, the comparison is made between the observed data (input) and the simulated data (output). This examines whether the basic input settings suggested in section 7.3.7 and default object properties from ENVI-met database significantly alter the inputted microclimate data. If there is no large difference between observed and simulated data, then, the basic input setting suggested in section 7.3.7 as well default object properties are reasonable to use for creating the model representing reality.

7.4.1. Important questions

One main question in the model evaluation:

"How much is the ENVI-met model accurate with reality by applying suggestion from section 7.3.7 and default object properties provided by ENVI-met database?".

The gap between model and reality (section 7.4.2) determines whether the model is accurate. In addition, the model evaluation attempts to investigate other important questions:

1. What is the possible cause of the difference between model and reality, and is it possible to reduce the difference? – The model calibration is demonstrated to answer this question in section 7.4.6
2. Does the larger site produce more accurate results compared to reality? – Two models of Kelburn weather station with different site size are compared to the measured data in section 7.4.7.
3. Can the airport weather data be inputted in ENVI-met model to recreate microclimate data like the Kelburn weather station? – In this experiment, the microclimate data from the airport station was inputted to the Kelburn weather-station model in ENVI-met. The output data from this was compared to the measured data of the Kelburn weather station to see difference. This aims to see whether the Kelburn model in ENVI-met can alter the generic weather data from the airport to be like the measured data of the Kelburn site. In this case, the altitude between the airport and the Kelburn site is largely different by about 125m, and this leads to the air temperature difference between those two sites. This can be an issue because ENVI-

met does not take account of the altitude factor in modelling microclimate. Section 7.4.8 investigates this issue through simulation testing in ENVI-met.

7.4.2. Quality assurance: Acceptable difference between simulation and reality

There are the number of studies that have validated ENVI-met model by comparing the simulated data against observed data. Mostly, they used Index Agreement (d) and or Correlation Coefficient (R^2) measures to match the simulated data against reality. One of the most variable outputs used for model validation is hourly air temperature data. A study by Salata, et al. (2016) collects the information of other studies validating ENVI-met using that approach. Most of those studies state that their model has been validated since the simulated data and field measurement have "good" correlation or agreement with mostly d or R^2 value of more than 0.8. However, such an approach is not relevant for model evaluation in this research because it does not relate to the energy modelling. For example, it is unknown whether R^2 of 0.9 for comparison of hourly air temperature would significantly affect energy simulation results. Thus, it is important to discuss the importance of air temperature gap to determine acceptable difference for model evaluation.

Section 7.3.3 used parametric tests to investigate the importance of air temperature difference on energy simulation results. It was found that lower air temperature of average 1^oC from midnight to 8 am increased heating energy by 9.6%. One study (Ca, et al., 1998) in Japan reveals that the air temperature above 1.2m above the green area (grass) can be lower than that above asphalt ground by about 2^oC, and this cooling effect can reduce the cooling load by about 15% during the summer in urban areas. This finding is slightly larger than that found by previous studies (Kanopacki, 1996) (Taha, et al., 1997) which showed that the reduction of air temperature by 1-2^oC (around 2 pm) leads to energy saving for air-cooling up to 10%.

One study (Bowler, et al., 2010) analysed data from numerous empirical studies about the cooling effect of parks and showed that parks have cooler temperatures than their surrounding (street or urban sites) averaging 0.94^oC during the day (6am to 8pm) and 1.15^oC at night (8pm to 6am). This indicates that a cooler air temperature of about 1^oC approximates the cooling effect produced by parks.

An additional test was conducted to investigate the impact of ground surface on air temperature. This test simulated four models, each of which had different ground surfaces over the whole area: Dark Pavement, Asphalt, Grass and Loamy soil. The site geometry is flat and open with one receptor in the middle of the model area, and used the same basic input parameters as the

Kelburn model (described in 7.4.4). The test aims to see whether the ENVI-met model matches with the analysis results showed by Bowler, et al. (2010

Diagram 7.63 shows the simulated data for four different ground surfaces. The asphalt, grass and loamy soil produce similar results while only the pavement dark gives significantly higher temperatures, averaging 0.9°C over the whole day.

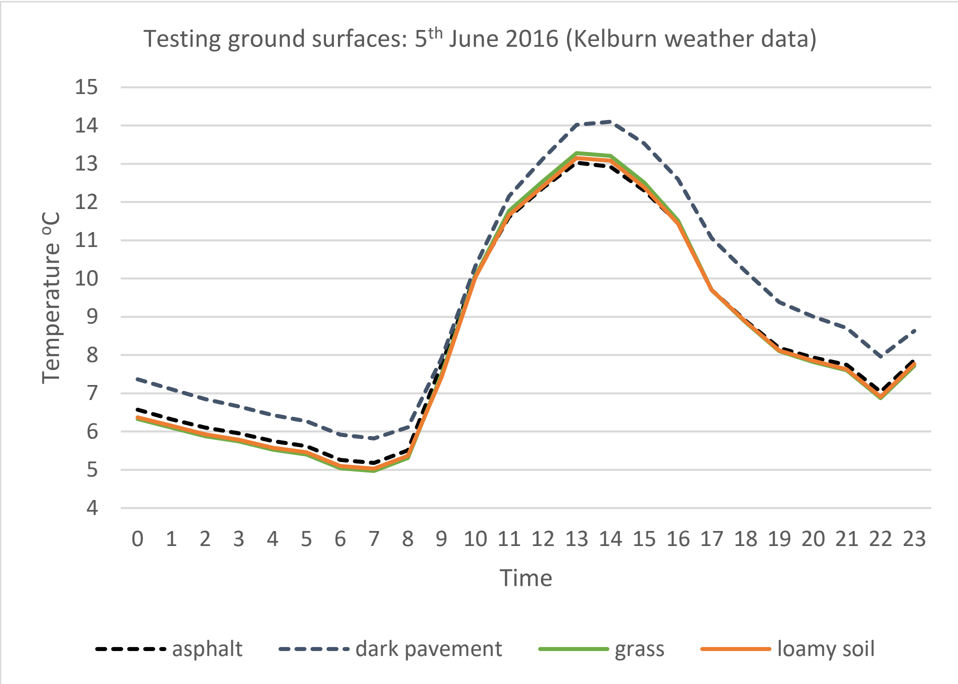


Diagram 7.63. The impact of ground surface on air temperature in ENVI-met model

Meanwhile, the asphalt model produces similar results to the grass model, with the largest difference of no more than 0.1°C. The ENVI-met asphalt material does not match with the results from Bowler, et al. (2010), suggesting the asphalt material from ENVI-met database might not represent the asphalt in the real world.

The findings from section 7.3.3 and analysis results from Bowler, et al. (2010) suggests that the importance air-temperature difference by 1°C between simulated and measured data cannot be underestimated. First, as noted it can significantly affect the energy simulation results by nearly 10%. Second, in the context of ENVI-met model, such a difference equals to the replacement of natural surface e.g. grass with dark pavement, which indicates a discrepancy of ground-surface properties between model and reality. Therefore, for model evaluation in ENVI-met, the average air temperature difference by less than 0.5°C between simulated and measured data can be considered acceptable.

7.4.3. Limitations in the model evaluation: Solar radiation input

One of the limitations of the ENVI-met basic version in the process of evaluating or calibrating the model is the solar radiation input. As explained in section 7.3.1, ENVI-met generates the solar radiation in the model based on the latitude and longitude coordinates and it cannot input the solar radiation based on the weather data.

Figure 7.6 shows the basic input settings which are provided in ENVI-met. In terms of solar radiation input, the two input features can be only modified through the basic setting and configuration.

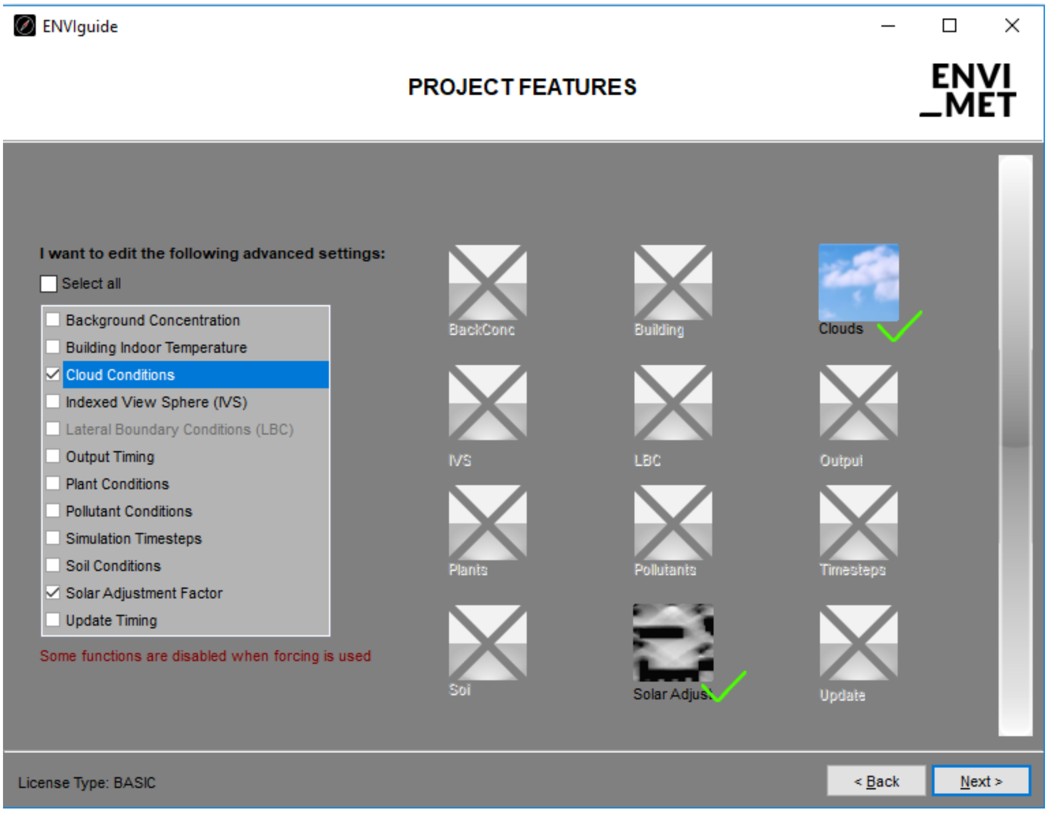


Figure 7.5. Advanced setting in the basic setting and configuration (ENVIguide)

Figure 7.6 shows the adjustment factor for the solar radiation setting while Figure 7.7 shows the cloud cover setting in ENVI-met. Both are based on a factor or fraction value. This means that ENVI-met is limited to model a fixed solar radiation which is influenced by the change of cloud cover. In reality, the sky can be cloudy in the morning then sunny (Clear) in the afternoon. Moreover, the default setting in ENVI-met applies 1.0 (clear sky) for the solar radiation input.

"Normally ENVI-met is run for cloud-free sky conditions as in this situation the spatial and temporal differences can be observed best" (ENVI_MET, 2017e). Previous studies (Salata, et al., 2016) (Skellhorn, et al., 2014) (Middel, et al., 2014) also validated and calibrated the ENVI-met's simulated data with observed data based on the cloudless condition. Therefore, the date selection in the basic configuration should be based on a sunny day (clear sky condition) in order to easily match the simulated data with the real data (cloudless day) in the model evaluation and calibration.

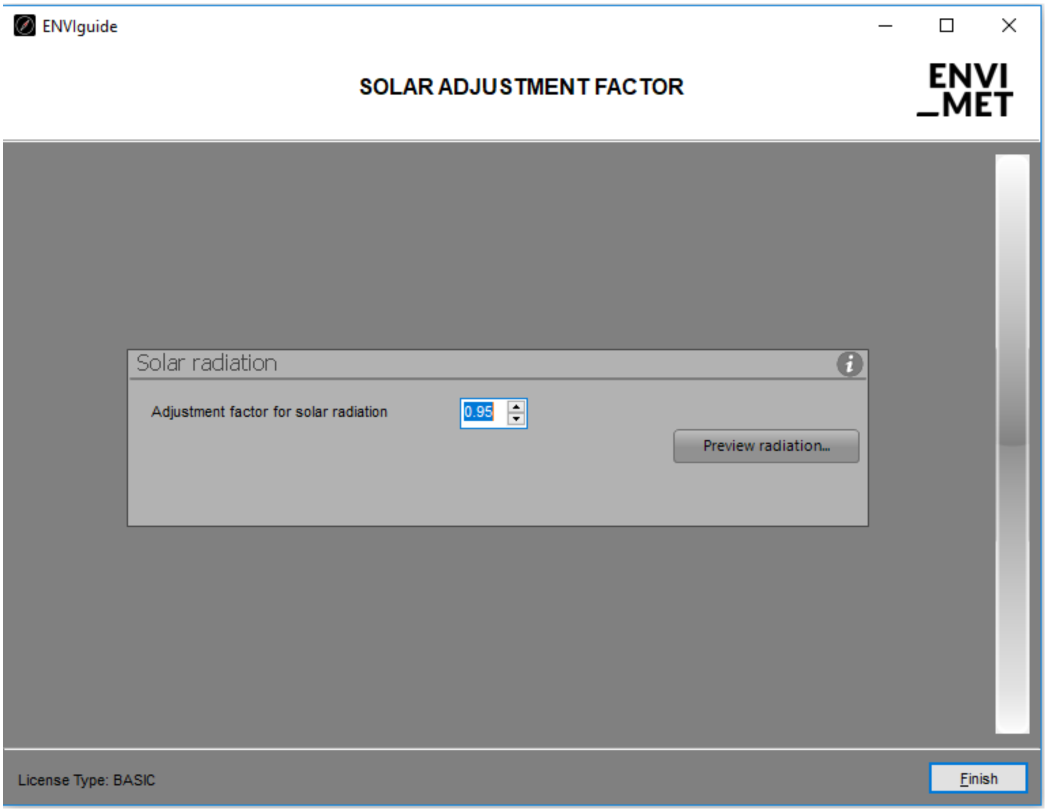


Figure 7.6. Adjustment factor for solar radiation in ENVI-met

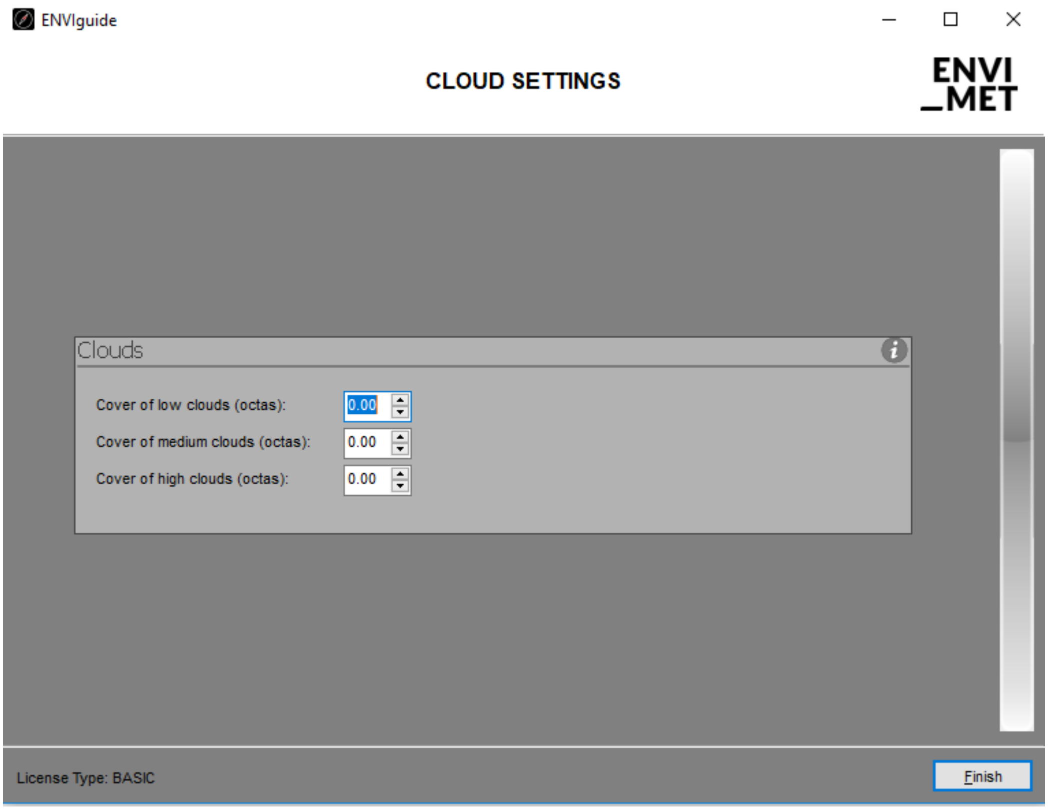


Figure 7.7. Cloud settings in ENVI-met

7.4.4. Study case: Kelburn weather Station Wellington

The site of Kelburn weather station is used as a study case to evaluate the simulated data. This site is surrounded by garden area and is located about 800m from the city centre in Wellington with 125m of elevation above the sea level (Figure 7.8). The site is above the hill and it is relatively open conditions (unobstructed) within the radius of 20m from the weather station device.

Figure 7.8. The situation of Kelburn weather station (Via Google Earth)

As discussed in section 7.4.3, one important consideration in model evaluation is the date selection for the sunny day which can match the solar radiation between the model and reality. Diagram 7.64 compares the hourly solar radiation from ENVI-met and Kelburn weather station in three sunny winter days between June and July 2016. Overall, both modelled and observed data have a similar value of global radiation, but they differ in the terms of direct and diffuse solar radiation values.

The direct solar radiation in ENVI-met model is higher than that in the field measurement while the diffuse solar radiation in the model is lower. The lower hourly value of direct solar radiation in the weather data is possibly due to atmospheric turbidity (gases and suspended particles), which absorbs, scatters and reflects the direct solar radiation before reaching the earth's surface (Solaimanian & Kennedy, 1993). This indicates that either the real site has higher atmospheric turbidity than the model, or ENVI-met does not take account of atmospheric turbidity in its solar radiation calculation.

This model validation uses a flat-open area (unobstructed) weather-station site. Thus, all ground surface area is likely to receive the similar amount energy of solar radiation since both ENVI-met and measured data have similar values of global radiation. Section 7.4.5 shows the results of model evaluation of weather station site and this gives the answer whether the discrepancies of solar radiation in ENVI-met leads to significant difference of air temperature between measured and simulated data.

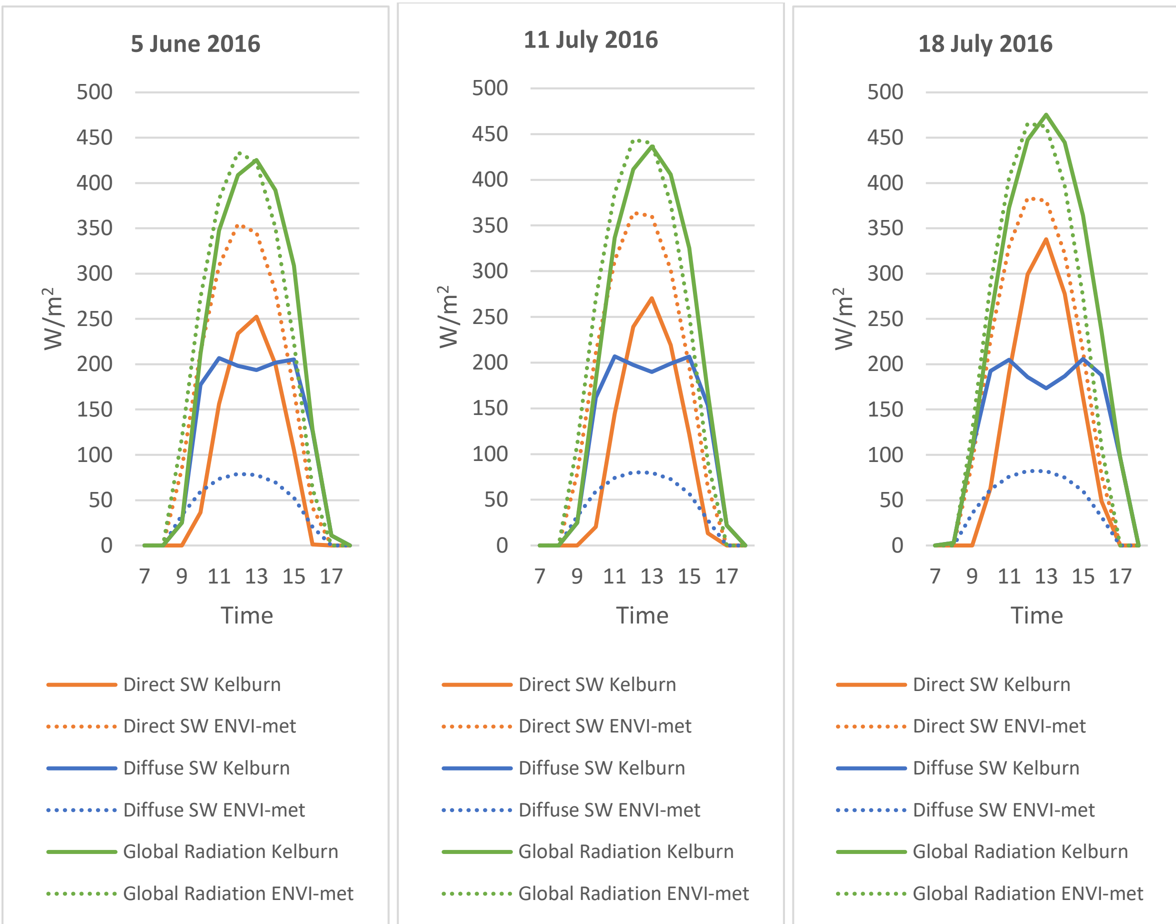


Diagram 7.64. Solar radiation between ENVI-met model and Kelburn weather station (NIWA) in sunny days of winter

The 5th June 2016 was selected for model evaluation. The simulation period was set from 4th June, started from 18.00, with 72 hours of simulation duration. Then, the last 24 hours data (5th June) was analysed. The model applied 1m grid with 50x50x25 of grid cells. Wind speed and the roughness value are 0.8ms^{-1} and 0.01 respectively (see section 7.3.7). The wind direction was set by 0^{o}. The hourly air temperature and RH were inputted in the simple forcing tool.

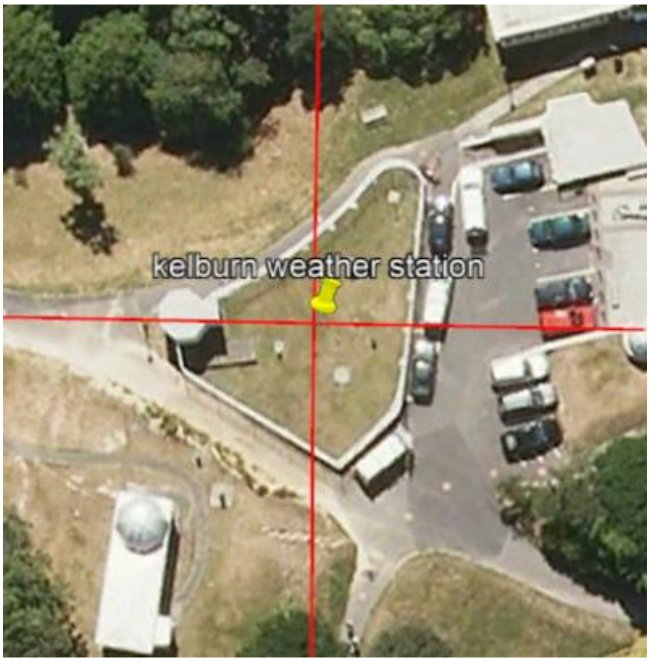


Figure 7.9. Kelburn site: 50m x 50m area (Via Google Earth)

Figure 7.9 shows the site area (50mx50m) of Kelburn weather station which was modelled in ENVI-met while Figure 7.10 depicts the model of Kelburn weather station in ENVI-met. The input of site parameters is described below:

- Building Object. (grey colour). The number marked in the building block shows the building height. For example, the building located in the northeast from the receptor is 4m in height.
- Soil surface. The white block represents the asphalt area in the model while the loamy soil is set in the green area (below the plants model).
- Plants. The grass is depicted with the light green blocks (20) while the pure green (TK) is for the trees. The height of the grass and trees is simplified by 20cm and 8m respectively while other properties follow the ENVI-met default value such as Leaf Area Density (LAD), Albedo, etc.
- A receptor (k1) is located in the middle of the site model.

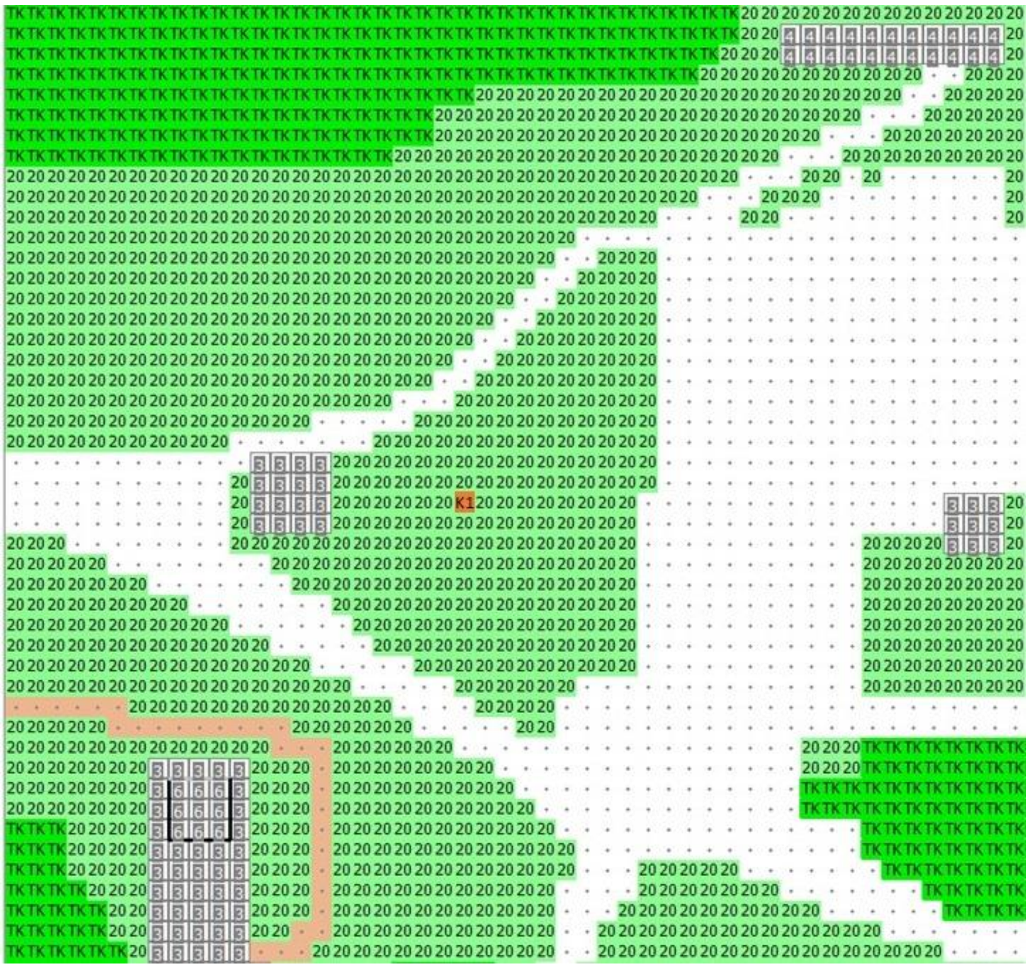


Figure 7.10. Kelburn-site model (50x50x25 cells)

7.4.5. Evaluation: ENVI-met model vs reality

Diagram 7.65 compares the hourly air-temperature data produced by base ENVI-met model and Kelburn measurement (NIWA) on 5th June 2016.

Overall, the ENVI-met generated data file has lower hourly air-temperature values than that of field measurement. Both model and reality have similar air temperature in the first ten hours, although the model is slightly higher by an average of by 0.1^{o}C. Around the midday (11am to 2pm), the simulated data is lower than the field measurement by 0.8^{o}C on average. The gap narrows to be 0.3^{o}C on average from 3pm to 11pm.

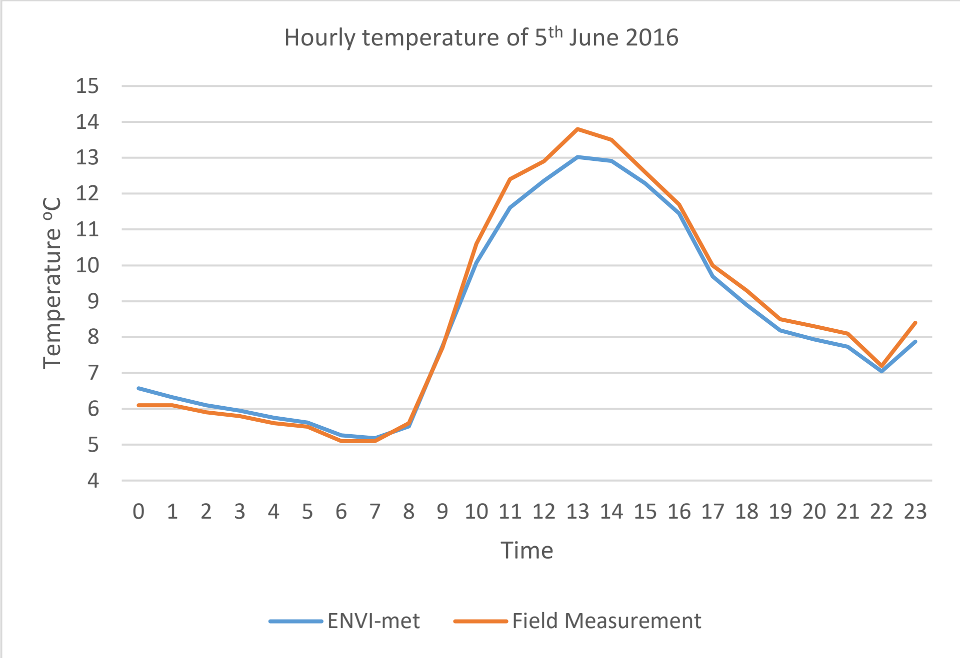


Diagram 7.65. Comparison between simulated data and field measurement on Kelburn weather station

Based on section 7.3.3, those differences will not affect any results of house heating energy simulation for Wellington house. This suggests that the basic input parameters suggested in section 7.3.7 and default object properties used in this model can give similar results to the measured data.

However, as discussed in section 7.4.2, the difference of 0.8°C around midday is likely to indicate a discrepancy of either ground-surface properties or solar radiation (addressed in section 7.4.4). A model calibration was conducted to examine the cause of this discrepancy and improve the model, which is discussed in the next section (7.4.6).

7.4.6. Model calibration

Through the calibration process, the possible site parameters causing differences can be investigated, and the simulated data improved. This can be useful information to allow the model producing more accurate results. This section calibrates the Kelburn-site model using the 1m grid with 0.8ms^{-1} wind speed.

7.4.6.1. Possible causes of the difference between the model and reality

As shown by the Diagram 7.65 the from section 7.4.5, there is a significant difference between the simulated data and field measurement, where the model has lower air temperature around the midday (11am to 2pm) of 0.8°C. There two possible site parameters that can be altered to increase the hourly air temperature, especially during the midday and evening:

1. The asphalt surfaces. The asphalt material in ENVI-met model does not increase the air temperature, which is not in accordance with the empirical studies (See section 7.4.2). But, the dark pavement in ENVI-met leads to warmer temperatures, which matches analysis results. Thus, replacing asphalt with dark pavement material is likely to increase the model hourly air temperatures.
2. Tree objects in the north area. Trees objects are placed about 18m from the receptor. They are likely to reduce air temperature during the daytime in the middle area as they can block direct solar radiation to the ground. As described in section 7.4.4, ENVI-met has much higher value of the direct- than diffuse- solar radiation (see Diagram 7.65). This is likely to lead a discrepancy between the model and reality during the midday. Besides, the existence of tree objects in the model can be an issue in comparing the model and reality because the hourly air temperature inputted to the model has been affected by tree shade. In other words, the simulated data of Kelburn model is affected twice by tree objects, and this is not comparable with reality. Therefore, removing the tree objects on the north of the receptor is expected to increase the hourly temperature during the midday in the model.

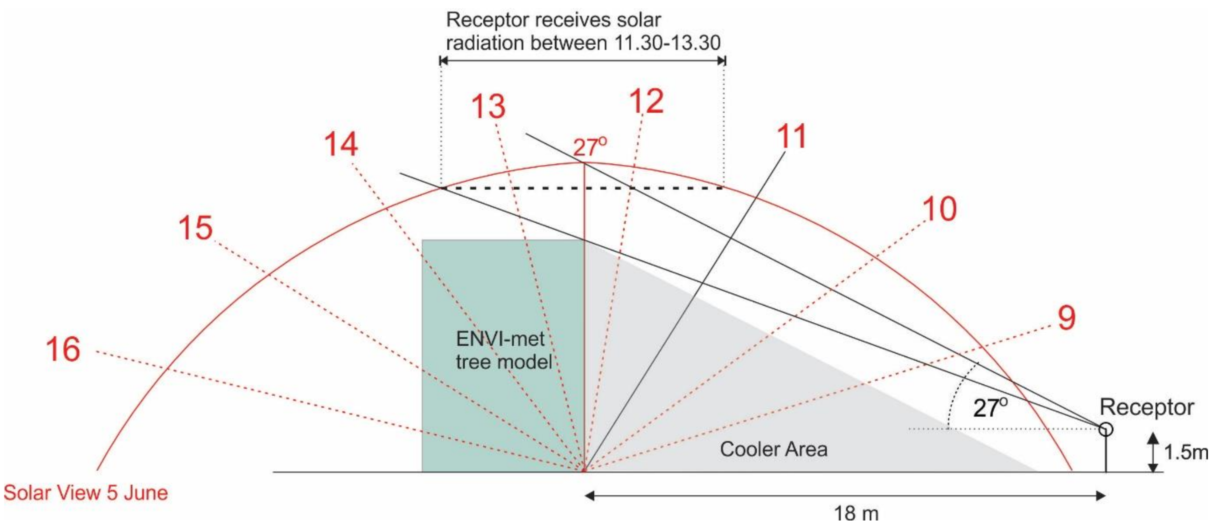


Figure 7.11. Tree shade (North) in the Kelburn site model

7.4.6.2. Steps of model calibration

Figure 7.12 shows three scenarios for model calibration based on discussions from section 7.4.6.2.). Each scenario investigates the influence of each factor and synchronize the model with the real environment.

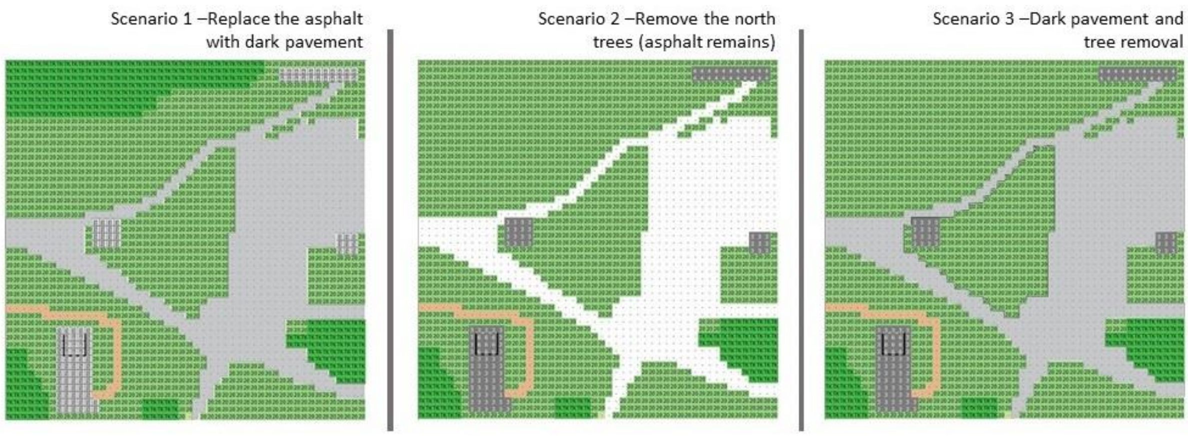


Figure 7.12. Scenarios for model calibration

7.4.6.3. Results and discussion

Diagram 7.66 shows the simulation results of scenario 1 where the asphalt material in the model is replaced with dark pavement material. Overall, this replacement leads to an average increase by 0.4°C from midnight to 8am and 0.2°C in the rest of the evening (from 5pm to 11pm). Nevertheless, there is a tiny increase around midday (11am to 4pm) by no more than 0.1°C.

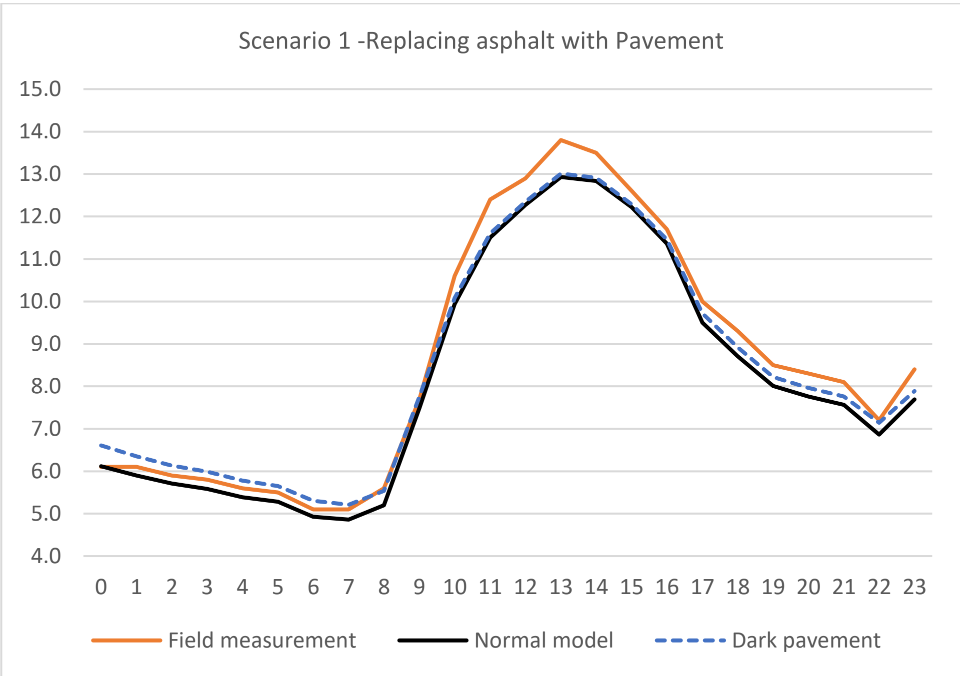


Diagram 7.66. The results of scenario 1 of model calibration –Replacing asphalt with dark pavement

Diagram 7.67 shows the simulation results of Scenario 2 where the tree objects in the north side are removed. In general, the hourly air temperature goes up in the rest of the day, and the difference between this model and measured data becomes much smaller, especially around the midday (from 11am to 2pm) by 0.3°C on average. The difference of hourly air temperature during the evening (from 5pm to 11pm) becomes much narrower, which is by about 0.1°C.

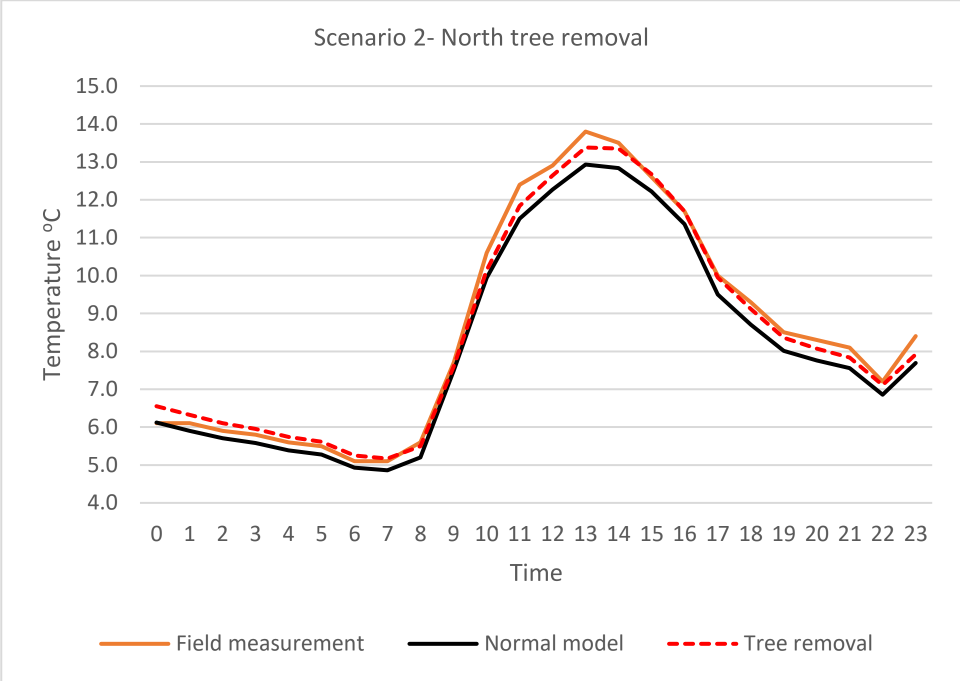


Diagram 7.67. The results of scenario 2 of model calibration –North tree removal

Scenario 3 combines the site modification of scenario 1 and 2 of model calibration. As can be seen in Diagram 7.68, Scenario 3 produces the same output as Scenario 2 with the average difference of 0.3°C around the midday (11am to 2pm) and 0.1°C in the evening (5pm to 11pm) compared to the measured data.

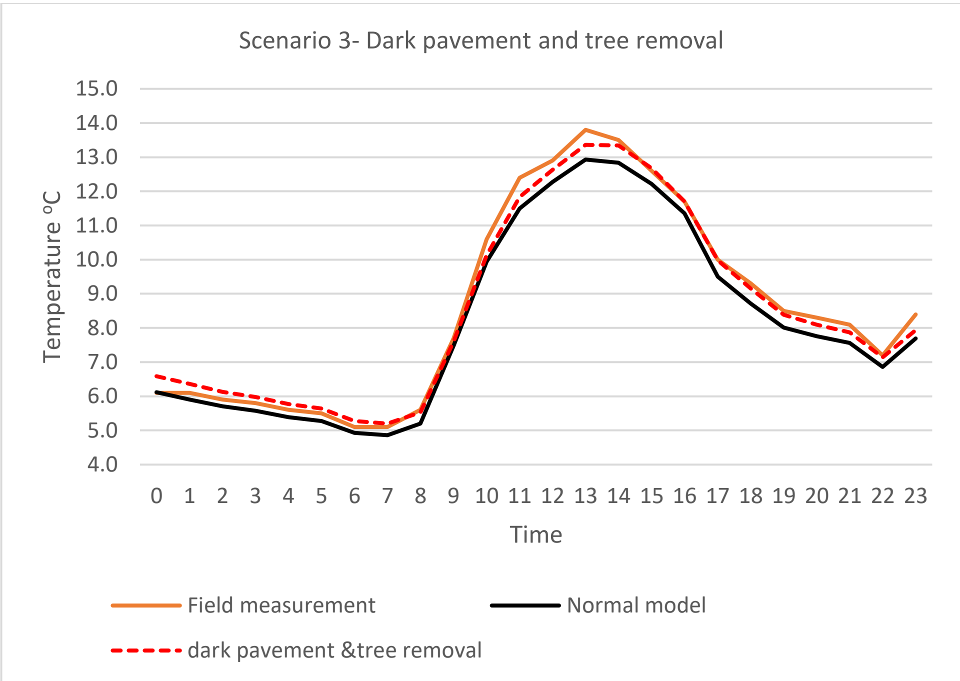


Diagram 7.68. The results of scenario 3 of model calibration –Dark pavement and north tree removal

Scenario 1 and Scenario 3 indicate that that the dark pavement is not as important in modifying the receptor air temperature as the removal of the north side tree objects. This might be because of two factors: (1) the receptor in the Kelburn model is still in the grass area which cools the temperature, and (2) the proportion of dark-pavement surface in the Kelburn model is much smaller than that in the additional test from section 7.4.2 (100% dark pavement).

The model calibration reveals that the tree objects in the north side of the receptor is the main cause of the difference between simulated data and field measurement. This can be seen in Scenario 2, which produces much closer data towards field measurement with an acceptable gap.

7.4.6.4. Lessons and suggestions

The calibration process shows that the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models. The model is affected twice by the tree objects -once from real environment through the input measured data, and secondly from the tree model. That condition leads to the bigger difference around the daytime between simulated and measured data as the tree models blocks the direct solar radiation from the north side. Scenario 2 (see Diagram 7.67) produces results closer to the measured data after removing the tree objects, compared to Scenario 1 (see Diagram 7.66). This suggests that attention is required to ensure the simulated and measured data is comparable in evaluating and calibrating the ENVI-met model. Also, the discrepancies of solar radiation in ENVI-met can lead to a difference between measured and simulated data in the midday depending on tree-shade coverage and location.

Small differences in the calibrated model (Scenario 3 – see Diagram 7.68) average 0.3°C around midday and 0.1°C in the evening indicate the likelihood discrepancies of ground-surface materials between ENVI-met and real condition. However, such a difference is not important as it does might affect the results of energy calculation in BES by less than 2% (section 7.3.3). Therefore, ground-surface types used in the model such as loamy soil, grass and asphalt are reasonable to use for further simulation as they do not affect the simulation results significantly.

However, the difference between uncalibrated model of weather-station site (Scenario 1– see Figure 7.12) and measured data can be also considered not important as such a difference does not affect the simulation results in BES more than 5% (based on analysis from section 7.3.3). This model is used further to investigate the impact of domain area on accuracy in the next section 7.4.7.

7.4.7. Impact of model domain area on accuracy: Medium Vs Large model

A large model of Kelburn-site model is created and tested to investigate the impact of domain area on accuracy. Figure 7.13 depicts the area of Kelburn-site (the 1m grid with 100mx100mx35m) modelled in ENVI-met.

The building object is depicted in a grey colour while the white represents the asphalt area in the model. Grass is depicted with the light green blocks and the pure green is for the trees (8m). The surface is set as loamy soil for the green areas and the receptor placed in the middle of model.

Figure 7.13. Large model of Kelburn weather station: 100m x 100m (Left: Image from Google Earth, right: ENVI-met model)

Diagram 7.69 compares the simulated data from the 1m grid-size model with the normal (50mx50mx25m) and large sizes (100mx100mx35m) and the observed data. In general, the normal and large model has a similar the temperature difference between the model and reality averages 0.8^{o}C around the midday because of the nearby tree models the temperature difference between the model and reality averages 0.8^{o}C around the midday because of the nearby tree models values of hourly air temperature. However, the hourly air temperature of the large model is higher than the measured data by about 0.5^{o}C on average in the first six hours while the difference between the normal model and measured data averages 0.2^{o}C in that time.

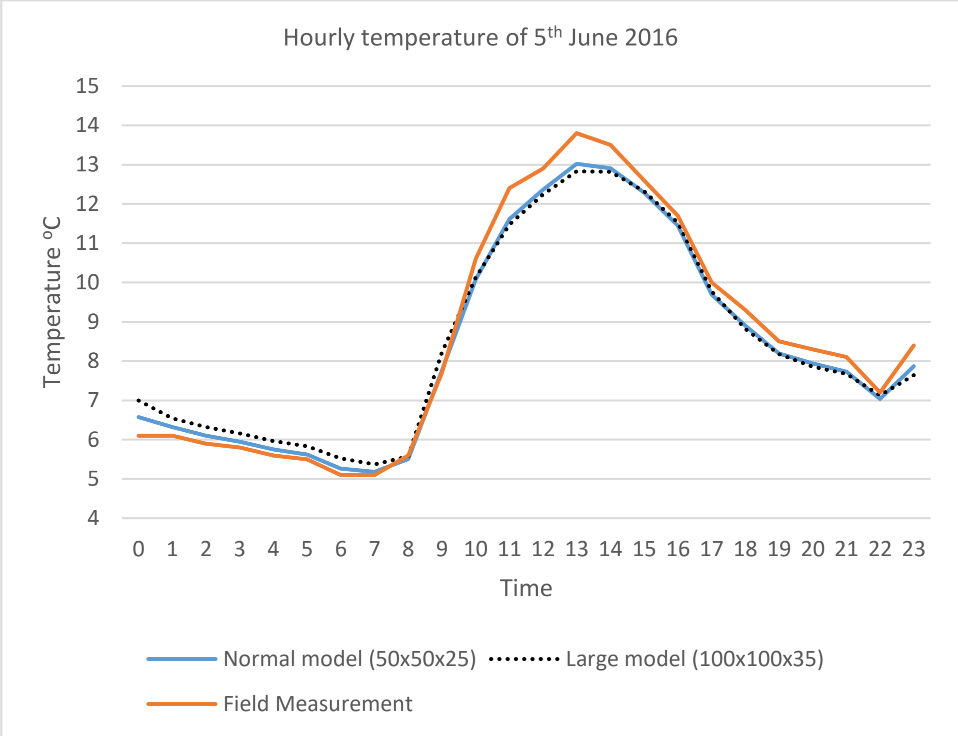


Diagram 7.69. Simulated air temperature of the normal mode and large model for Kelburn site model

The following table (Table 7.13) compares the computational time between the normal and large model of Kelburn-site model. Overall, the large model takes around six times longer than the medium model to simulate 18 hours of hourly data.

The 1m grid (0.8ms^{-1} of wind speed)	Domain Area	Computational Time
Normal model	50mx50mx25m	7h 8 min
Large model	100mx100mx35m	45h 45min

Table 7.13. The computational time between medium and large ENVI-met model

From testing the impact of model domain area, the normal model (50mx50mx25m) is preferable in modelling microclimate. First, it produces better results compared to the large model in terms of accuracy where the difference of air temperature in the first 6 hours is smaller (0.2°C) than the large model (0.5°C). As discussed in section 7.3.3, the bigger difference from midnight to 8am can lead to a bigger difference of the simulation results of heating energy while the difference by 1°C from 10 am to 11pm has no influence. This also suggests that the difference by 0.8°C around the midday for both models is not important. Second, it takes reasonable computational time, which is about 7 hours -Much faster than the large model taking about 45 hours.

7.4.8. Altitude issue in ENVI-met: Kelburn vs Airport weather data

As discussed in section 2.3.1, the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models every 100m increase in elevation the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models in temperature decrease by about 0.6°C the temperature difference between the model and reality averages 0.8°C around the midday because of the nearby tree models. Diagram 7.70 shows the hourly air temperature data of Wellington airport and Kelburn weather station on 5th June (sunny day), which at altitudes 13m and 125m respectively. During the daytime, the Kelburn site has a higher temperature by 1.0°C from 10am-1pm on average. Then, it is lower by 1°C on average between 3 and 7pm. The same trend also occurred on the 4th and 6th June (Diagram 7.71), where the Kelburn has lower temperature by 1.6°C on average over that time. From comparing the 3-days of hourly data between Wellington airport and Kelburn, both sites have similar air temperature around midday (between 11am-2pm) while the airport is higher by between 1-2°C after midday.

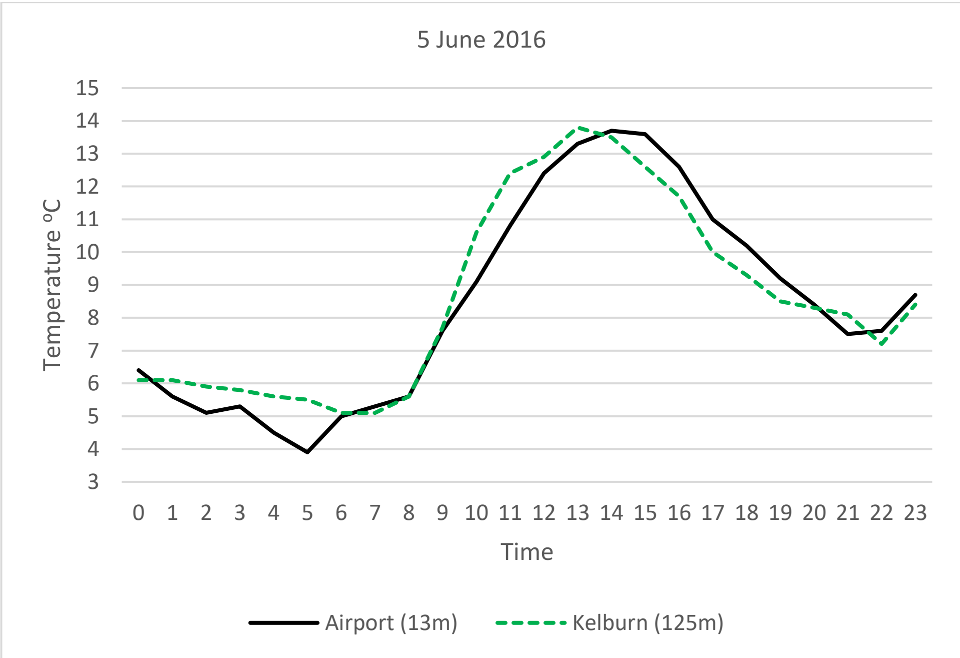


Diagram 7.70. Hourly air temperature data of Wellington airport and Kelburn (different altitude) on 5th June 2016

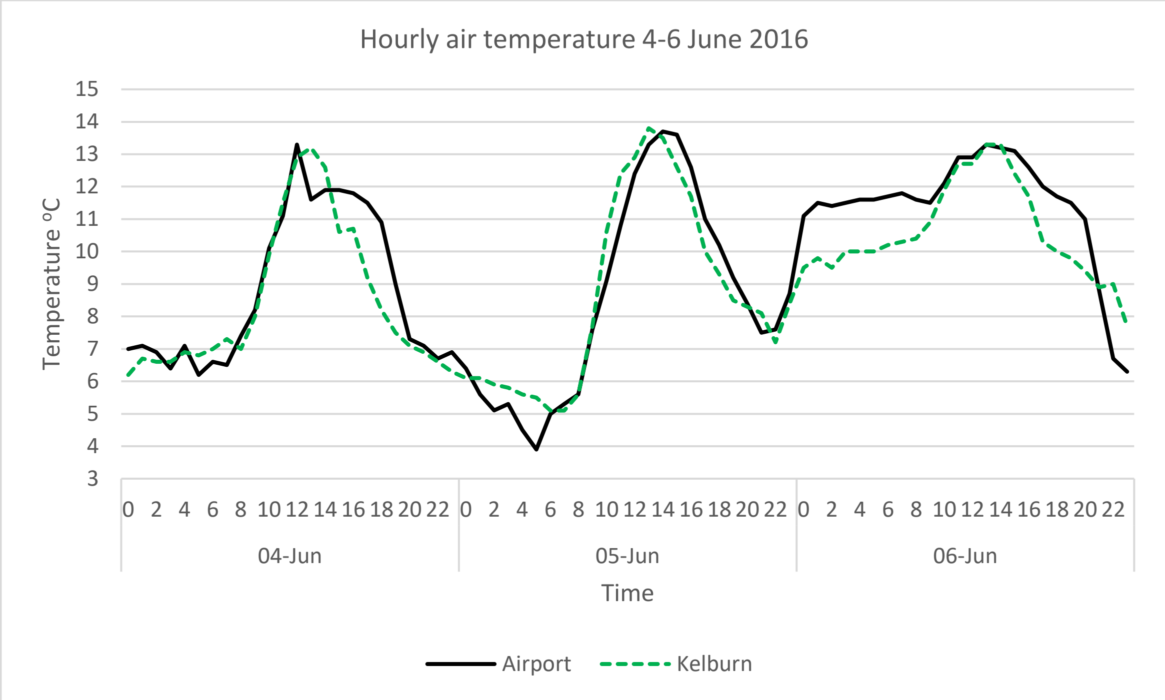


Diagram 7.71. Hourly air temperature data of Wellington airport and Kelburn between 4th-6th June 2016

An additional test was conducted to investigate how the ENVI-met Kelburn model behaves compared to the airport's air temperature and RH. The airport hourly weather data for 5th June were entered into the calibrated Kelburn model (scenario 2 -see Figure 7.12) since this model is comparable to the real condition of the weather-station site (open-flat) –discussed in section 7.4.6.3.

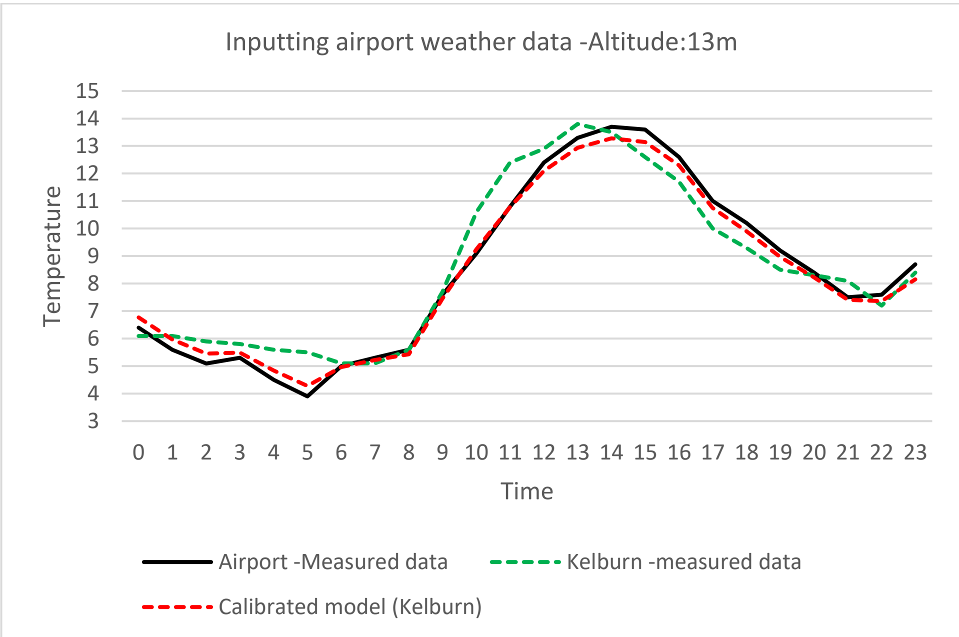


Diagram 7.72. Simulated data of Kelburn model based on the hourly weather data of Wellington airport

Diagram 7.72 reveals the simulated data of the Kelburn model inputting the hourly weather data from Wellington airport. Overall, the model produces a similar trend as the airport measured data (within ± 0.4°C).

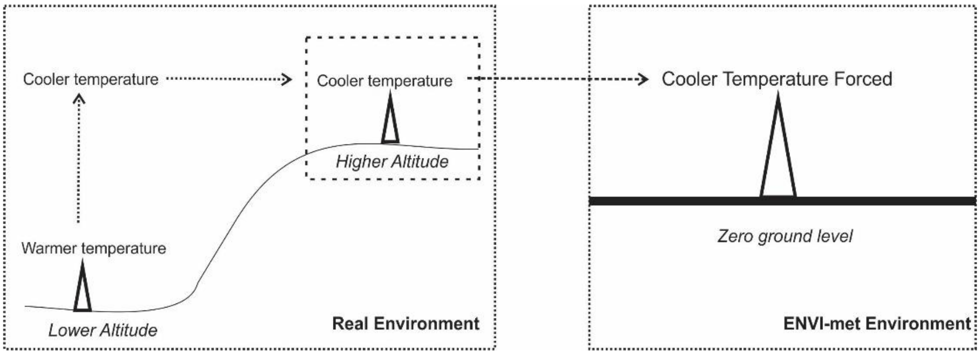


Figure 7.14. Altitude and relevant microclimate data in ENVI-met

As noted, ENVI-met does not take account site elevation or altitude. Therefore, it is not surprising that the Kelburn model using airport weather data does not match in the Kelburn measured data. This is because the air temperature and RH inputted to the ENVI-met model have been affected in the real world by the altitude change (see Figure 7.14). This suggests that the selection of microclimate data inputted into ENVI-met should note the site altitude in the model calibration or validation. For example, Wellington Airport is not appropriate for input as generic weather data for the site model in the Kelburn area since they differ in altitude. Importantly, this means that the application of ENVI-met for site modelling is limited for a hilly region like Wellington since it cannot rely on generic weather data from only one altitude.

7.4.9. Conclusion

In conclusion, it needs attention in comparing simulated and measured data for evaluating and calibrating the ENVI-met model. The model calibration must ensure those two data comparable. To make it comparable, some previous studies (Morakinyo, et al., 2016) (Salata, et al., 2015) (Skellhorn, et al., 2014) established the model of specific site (e.g. urban area, inner court or park area) by inputting generic microclimate data (nearby weather station) to recreate the specific microclimate data. Then, this specific microclimate data is compared to the on-site measured data from that specific site. In this case, the on-site measured data has been affected by nearby site parameters in reality while the specific simulated data has taken account of site parameters in the model. The aim of model calibration in those previous studies is to establish validated model to examine the site parameters impact e.g. the impact of high and low albedo material or green area.

However, this research conducted different approach of model calibration by comparing the real site and the model of weather-station site which is mostly flat and unobstructed. This approach was taken because it focuses on evaluating how significant the basic input parameters suggested in section 7.3.7 and default object properties in ENVI-met lead the difference between simulated and measured data. The standard for air temperature difference was discussed in section 7.4.2.

Through model evaluation it is found that the basic input parameters suggested from section 7.3.7 and the default object properties from by ENVI-met database are reasonable to use for further simulation as they lead the model closer to the measured data. The difference between the calibrated model and the measured data is no more than 0.5^{o}C. Moreover, the 1m grid with 50x50x25 cells (62,500m^2) can produce more accurate results compared to the larger domain area with shorter computational time.

As ENVI-met does not take account of altitude in the simulation (discussed section 7.4.8), it is important to record whether the microclimate data has similar latitude to the real site modelled. This suggests that the application of ENVI-met is limited for the hilly region like Wellington, which varies in altitude, since it cannot rely on the one generic weather data from only one altitude location.

7.4.10. Limitations of model evaluation

Some issues of ENVI-met model were found in the process model evaluation:

1. The ENVI-met basic (free) version cannot input the solar radiation input based on the weather file (discussed in section 7.4.3). ENVI-met generates solar radiation based on the longitude and latitude coordinates in clear sky condition (default condition). The hourly value of solar radiation can be only adjusted by a solar adjustment value – from 1.0 (clear sky) to 0.0. Thus, the model evaluation conducted in section 7.4 is based on the sunny day (clear sky condition). Moreover, there is a difference of the hourly value of direct and diffuse solar radiation between ENVI-met and the weather data (Diagram 7.64). The ENVI-met model has much higher direct solar radiation while the diffuse solar radiation is much lower compared to the weather data. This consequence of these differences is unknown.
2. One important issue related to validating or calibrating ENVI-met model is the validity of material or object in the ENVI-met database. As demonstrated in section 7.4.2, the asphalt material does not produce the heating effect which is as the literature review prediction, but another impervious layer, dark pavement, does. This raised the question of how closely the

materials and objects in ENVI-met database match with the reality so that the model can produce the trustable results – for example, whether the asphalt in the model can represent the asphalt in New Zealand. In addition, ENVI-met provides detailed property inputs in the ground material and tree object, which are difficult to determine for matching the real condition of site – for example, what is the water content value of soil material or the Leaf Area Density (LAD) of tree on the real site. There is also a lack of documentation about ther general assumption or physics explanation related to those detail inputs.

7.5. Conclusion and Output: the standard setting and configuration of basic input

Five basic input parameters were investigated through the parametric test (7.3) and model evaluation (7.4). These are: (1) grid size, (2) simulation period, (3) Wind condition input - meteorological basic setting, (4) domain area and (5) soil type.

There are three considerations in deciding the ideal value for those input parameters. The first is whether it can produce realistic model; second, how close the results are to the measured data; and third, computational time.

From the parametric test of basic input parameters and model evaluation, this research concludes that for modelling a house in Wellington, the:

- Grid size of 1m is preferable for simulation as it can create realistic model. In this case, it is the finest resolution that allows creating desirable object within the range of 1 to 10 metres. It also demonstrates realistic results related to the effects of building shade and surface heating (section 7.3.4.3)
- 30-hour simulation duration is more reasonable than the 72-hour simulation duration as both produce similar results for the last 24 hours overall. However, the 30 hours takes much shorter computational time (section 7.3.4).

- wind speed, direction and roughness value in the basic meteorological setting do not have any influence in heating or cooling the atmosphere (section 7.3.6). It is suggested that wind speed be set at $0.8ms^{-1}$ to avoid technical error during simulation (section 7.3.2.1).
- Section 7.4.7 shows that the model with the domain area of 50mx50mx25m (LxWxH) can produce results which are closer to the field measurement than the larger site (100mx100mx25m), as well as having a shorter computational time.
- Default soil type, Loamy Soil, is acceptable for simulation. The model calibration (section 7.4.6) shows that simulation results using Loamy soil had no significant difference to the measured data, (section 7.3.3).

With these conclusions, the standard setting and configuration of basic input for ENVI-met model is established. This will be applied to simulation evaluating the impact of site parameters on energy modelling in EnergyPlus.

Grid Size	1mx1mx1m (x,y,z)
Domain Area (cells)	50x50x25
Simulation Duration	30 h
Starting time simulation	18.00
Wind Speed	$0.8ms^{-1}$
Wind Direction	Default value= 0 or can be set any
Roughness value	0.1 for urban, 0.01 for suburban, 0.001 for open area or near sea (Stull, 1988)
Soil type	Loamy soil (Default)
Sky condition	Clear sky (Default)
Soil Condition	Loamy soil

Table 7.14. Setting and configuration of basic input for Wellington ENVI-met model for further simulation

8. Parametric study: site impact on heating energy use

This section investigates the impact of site parameters on the house heating energy modelling through integrating ENVI-met and EnergyPlus. Site scenarios were established in ENVI-met model in order to generate microclimate data as input to EnergyPlus. The parametric study examines the impact of air temperature and RH change on house-energy use, which is influenced by site parameters.

8.1. Key questions

There are two key questions in investigating the importance of site factors in this parametric study:

1. How important are the site parameters that cannot be modelled in EnergyPlus? The change of air temperature and RH resulting from site parameters impacts generated by ENVI-met were investigated. This gives the answer whether the idea of microclimate using ENVI-met is useful for site modelling in BES.
2. How much does microclimate data produced by ENVI-met through the use of different receptor directions influence heating load calculation in each building zone? Should the difference of microclimate data in different directions be considered in energy modelling?

8.2. EnergyPlus House Model

The design of EnergyPlus house model in this parametric study must answer the two key questions addressed in section 8.1.

8.2.1. Design and method

The house model was established consisting of four zones which interact with different orientation of outdoor microclimate, plus one internal zone. The EnergyPlus simulation was conducted by using four modified weather files based on ENVI-met microclimate data which are different in direction (North, East, South and West). The heating load of each zone is extracted after the EnergyPlus model run using the ENVI-met modified weather file. This extraction applies to other zones (see Figure 8.1).

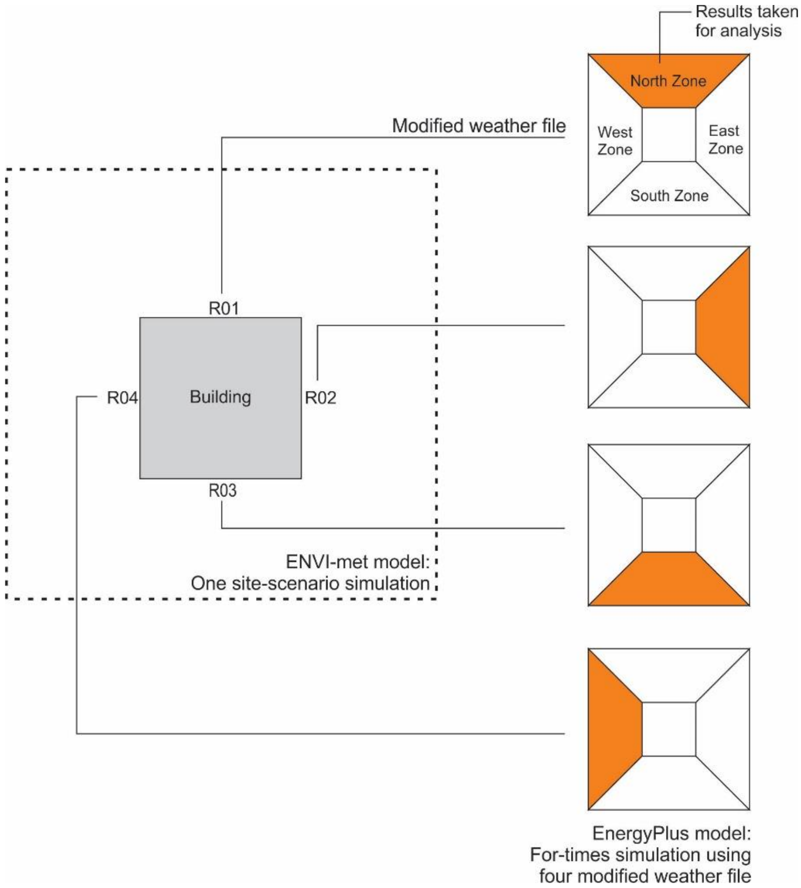
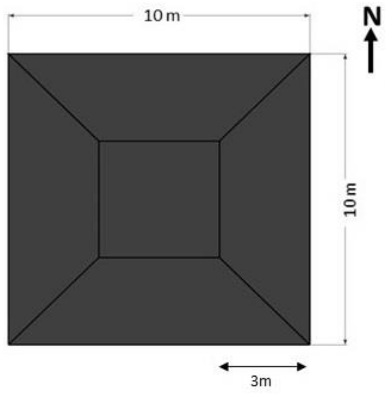
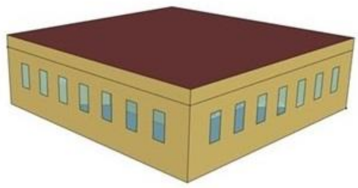


Figure 8.1. Design and Method for examining the importance of microclimate on energy modelling

8.2.2. Input and model description

The house size is 10m X 10m, 3m in height and consists consisting of five zones, with four zones analysed: (1) North zone, (2) East zone, (3) South zone and (4) West zone). All basic input parameters, including internal heat gain, construction, heating schedule, ventilation and infiltration used the same inputs applied in section 7.3.3. However, the house model in this section is assumed for four people living therefore each zone was input by one person except the middle zone. The total window area is 11.6% of total area of exterior walls, complying with NZBC Clause H1 requirements (no more than 30% window area), to use the Schedule Method in NZS 4218:2009 (Ministry of Business, Innovation & Employment, 2015). Figure 8.2 shows the model design and summarises the input parameters used in the model.





Heating Period	April-September
Schedule	Full day (00.00-24:00)
Heating set point	18ºC
Natural Ventilation set point	24ºC (Open if exceed setpoint)

Envelope	Climate Zone for Wellington
Roof	R 2.9
Wall	R 1.9
Floor	R 1.3
Windows	R 0.26

Internal Load	Watt	Schedule & Availability
Occupancy	75W per person	07:00-23.00 (60%) 23:00-07.00 (100%)
Equipment	16 W/m²	07:00-23:00 (25%) 23:00-07:00 (5%)
Lighting	8.5 W/m²	07:00-23:00 (15%) 23:00-07.00 (5%)

Figure 8.2. Design and Input of EnergyPlus model

8.3. ENVI-met microclimate modelling: Basic setting for the input

Microclimate modelling in ENVI-met generates one-day hourly data of air temperature and RH based on default Wellington weather data – Wellington WN 934360 (NIWA) - influenced by site parameter(s).

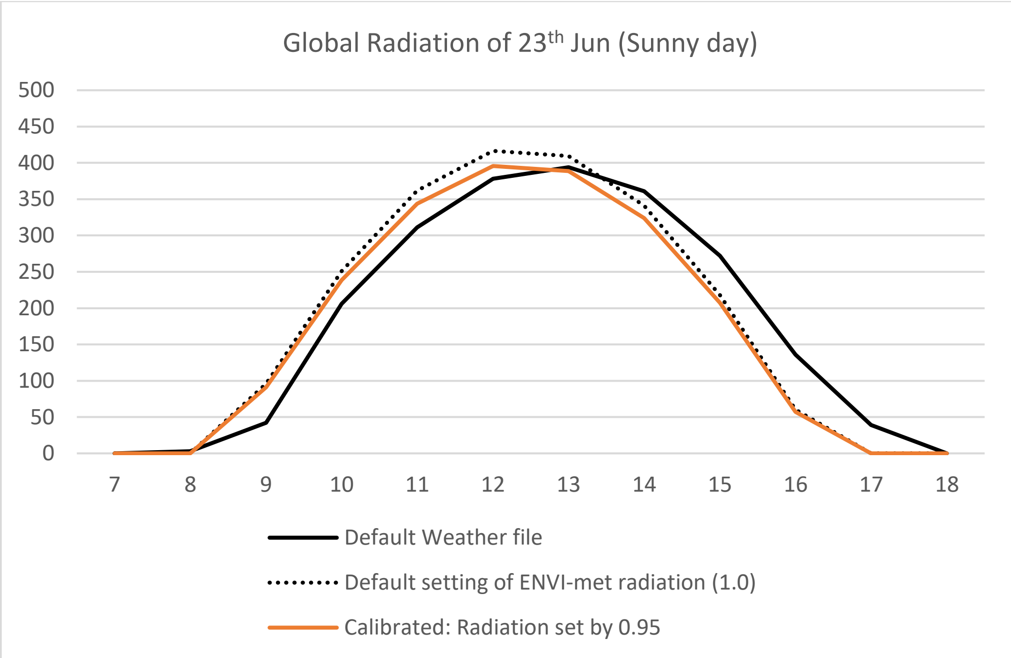


Diagram 8.1. Global radiation of 23 June both from default Wellington weather file and ENVI-met model

The date of 23rd June in the default Wellington weather file was selected for this parametric study as it relatively has clear sky condition, which matches with the sky condition in ENVI-met (section 7.4.3). The global radiation for this date from both from the weather file and ENVI-met were matched. The solar adjustment factor in ENVI-met was set by 0.95 (calibrated) to match the global radiation from the weather file.

The basic input parameters for the ENVI-met model (grid size, domain area, simulation period and wind input) based on the conclusion and suggestions from section 7.5 (see Table 7.14). The air temperature and RH data on 23rd June from Wellington weather data were applied using a simple forcing tool.

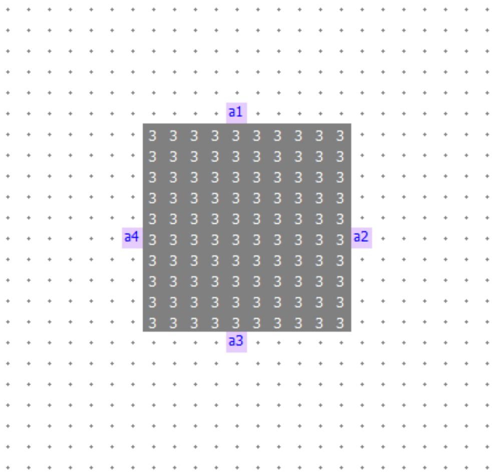


Figure 8.3. The building model and receptors in ENVI-met model

The size of the base building model 10m x 10m with the height of 3m and it is placed in the centre of the domain area. The four receptors were placed in front of each façade in the middle. In ENVI-met, receptor records microclimate data in the different height based on the grid centroid. For example, the 1m grid can record microclimate data of 0.5m (first grid centroid) and 1.5m (second grid centroid). In this test, the level of 1.5m was taken for EnergyPlus weather file modification. The site has no obstruction (plants or buildings) in the base ENVI-met model.

8.4. Site scenario for ENVI-met microclimate modelling

Table 8.1 summarizes 12 site scenarios for parametric study in ENVI-met. The scenarios are based on the site parameters that cannot be modelled in EnergyPlus: Interaction between plants, soil and surface.

Site parameters		**Scenario**
Terrain	Ground surface	(1) Loamy Soil
		(2) Full Pavement
		(3) 30% pavement on the East side
	Slope	(4) Facing-north slope(45°)
		(5) Facing-south slope (45°)
Vegetation	Number of Tree	(6) 12 trees in all direction (10m of height)
		(7) 60 trees in all direction (10m of height)
	Leaves	(8) 60 trees -Double LAD (leaf Area Density)

Buildings	Building shade	(9) Buildings in all direction (3m height)
		(10) Nearby buildings (6m height)
	Building surface	(11) Nearby buildings (3m height) high albedo
		(12) Nearby buildings (3m height) Concrete

Table 8.1. Site scenarios in ENVI-met model

Figure 8.4 illustrates the terrain scenarios in ENVI-met. There are two types of ground surfaces tested: Loamy soil (brown) and dark pavement. As can be seen from simulation results in section 7.4.2, the pavement surface in ENVI-met heats the air temperature while loamy soil, asphalt and grass produce similar air temperatures above ground. The heating effect resulted from the pavement was tested in the scenario 2 and 3 in Table 8.1.

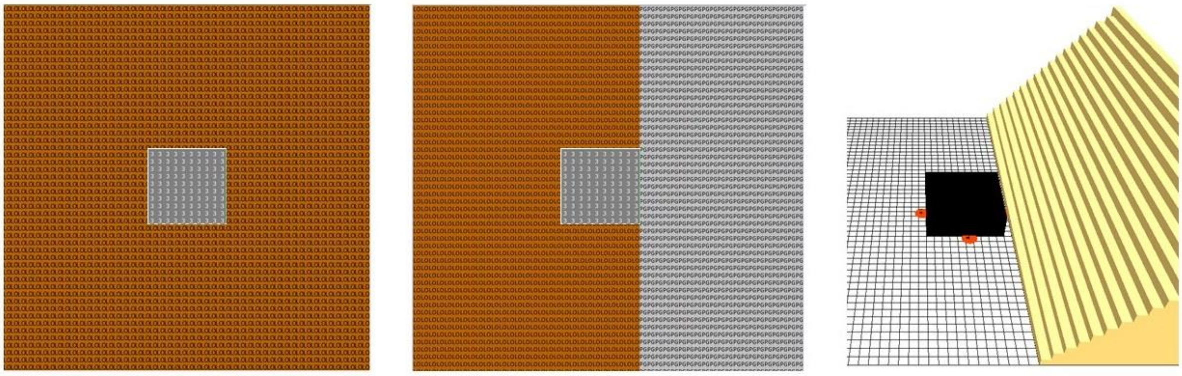


Figure 8.4. Loamy soil (Scenario 1), Pavement on the East side (3) and Facing-north slope (4)

Scenario 3 applies the dark pavement on the east side and loamy soil is on the other side. This aims to investigate how much the dark pavement heats air temperature on the other side. Meanwhile, Scenarios 4 and 5 test the impact of the slope. In ENVI-met, slope model is an integral part of the grid cell. As a result, the slope surface consists of vertical and horizontal surfaces (see Figure 8.4). There are two slopes scenarios tested: facing north (6) and facing south (7). The north slope is tested to see whether it produces the seasonal effect – a warmer temperature due to surface inclination facing equator, while the Facing-south Scenario might reduce the local outdoor temperature during the day due to its shading impact.

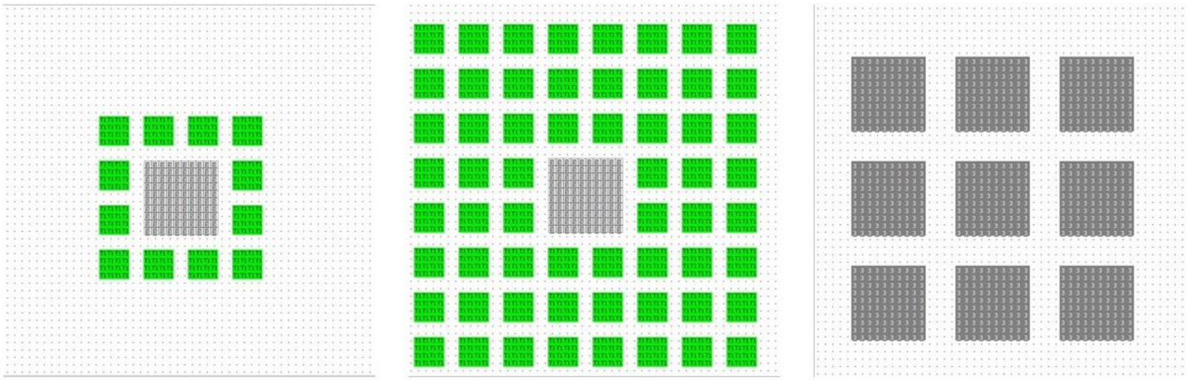


Figure 8.5. Tree scenario: 12 trees in all direction (6), 60 trees in all direction (7); and nearby buildings scenario (9-12)

Figure 8.5 illustrates the site scenarios for vegetation and nearby buildings. The tree scenarios test how much the number of trees (scenario 7) and tree-leaf density (scenario 8) affect house heating energy. Meanwhile, the nearby buildings scenario tests how much the building height, associated with outdoor shading (scenario 10), and building's façade (scenario 11 and 12) affect the heating energy. The reflection value in ENVI-met for both the scenario 9 and 10 are 0.4 while high albedo surface is 0.7 (Scenario 12). The scenario 11 uses concrete material, which is provided in ENVI-met database with 0.6 of reflection value.

8.5. Process of integrating EnergyPlus with ENVI-met

Figure 8.6 shows the process of integrating EnergyPus and ENVI-met. The weather file was converted by one of the EnergyPlus tool, Weather Statistic Conversion, then modified in the CSV file based on the results from ENVI-met simulation.

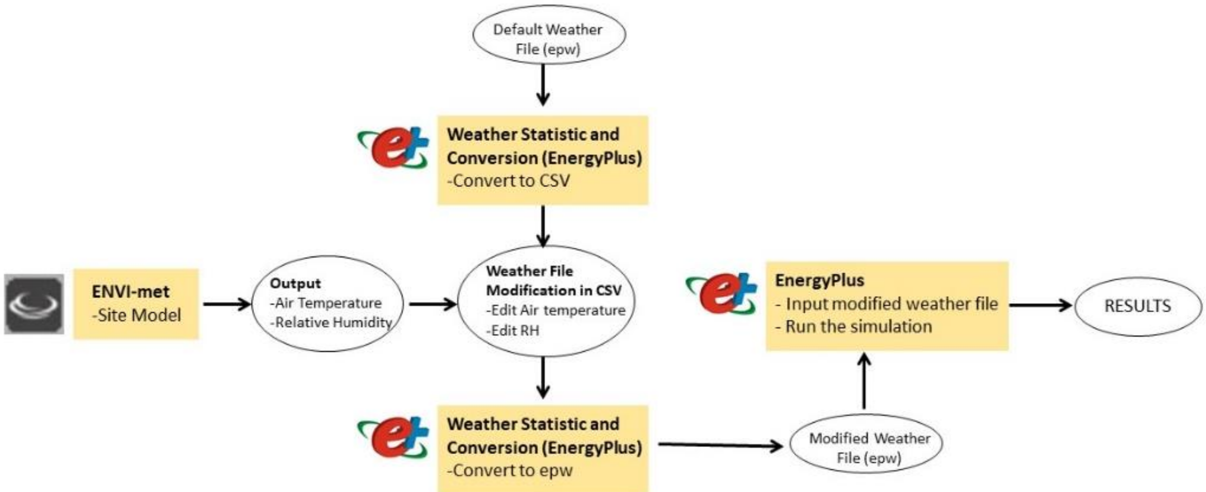


Figure 8.6. The detailed steps of integrating EnergyPlus with ENVI-met

8.6. Results and Discussion

Even though the results in this section are based on one-day modelling, it gives an initial answer of whether the site parameters that cannot be modelled in EnergyPlus are important. Table 8.2 shows, for 12 site scenarios, the additional house heating energy required on 23rd June for the four zones after inputting modified weather file based on microclimate modelling in ENVI-met. Almost all scenarios produce very similar results to the ENVI-met base model (Scenario 1- Loamy soil), with differences range from -6.9% to +1.0%. This indicates that almost site parameters modelled in ENVI-met have insignificant impact (as defined in section 7.1) on house heating energy calculation in EnergyPlus simulation.

Scenario	Total for all four zones (WH)	Difference to base (%)
Default weather file	27714	-3.1%
(1) ENVI-met Loamy soil (Base model)	28612	0%
(2) Full pavement	26652	-6.9%
(3) Pavement on the east side	27935	-2.4%
(4) Facing-north slope	28901	1.0%
(5) Facing-south slope	27152	-5.1%
(6) 12 trees in all direction	28433	-0.6%
(7) 60 trees in all direction	28289	-1.1%
(8) 60 trees- Double LAD	28184	-1.5%
(9) Nearby buildings (3m height)	28159	-1.6%
(10) Nearby building (6m height)	28497	-0.4%
(11) Nearby buildings (3m height) -High Albedo	28275	-1.2%
(12) Nearby buildings (3m height) -Concrete	27918	-2.4%

Table 8.2. House heating energy (23rd June) based on 12 site scenarios from ENVI-met

Based on Table 8.2, the importance and issue of site parameters are discussed below:

- **ENVI-met base model -Scenario 1: loamy soil.** It has the same condition as the default-weather-file scenario, which is open-flat (unobstructed). The difference between both models is small, which is only 3.1%. This result suggests that the Base model of ENVI-met (Scenario 1) is reasonable to use as it does not lead to significant difference (no more than 5% as defined in section 7.1) compared to the model using weather file.
- **Ground surface.** House heating energy in Scenario 2 (Full pavement) reduces significantly by 6.9% due to the heating effect of pavement as the ground surface. This matches with the literature review findings, discussed in section 7.4.2. As would be expected, scenario 3 with

less pavement area has smaller energy-use reduction than the full pavement area (Scenario 2), which is only 2.4%.

- **Slope.** The facing-north slope produces a similar result compared to the base model, which is higher by only 1%. This indicates that the slope in ENVI-met model does not produce the seasonal effect (Olgyay, 1963), which can lead to warmer outdoor air temperature and reduce the heating load. On the contrary, it produces higher heating load which indicates cooler outdoor temperature. Meanwhile, the facing-south slope has 5.1% less house heating energy, and this is also contrasted to the literature-review findings. Supposedly, south-facing slope increases the heating load as the outdoor air temperature reduces due to slope shading during the midday.
- **Tree.** All scenarios of the tree (Scenario 6, 7 and 8) have insignificant influence (less than 1.5%) on heating load calculation. In contrast to literature-review findings, these have a lower heating load. The increase of tree numbers and leaf densities in ENVI-met model (scenario 7 and 8) leads to very small heating load reduction (no more than 1% compared to the scenario 6). It was expected the ambient temperature would be cooler due to the number of trees and leaves intercepting solar radiation (Goulding, et al., 1992) as well as evapotranspiration effect (Berner, et al., 2005).
- **Nearby building.** All scenarios of nearby buildings produce insignificant impact, with slightly less heating load than the base model (Scenario 1). However, Scenario 10 shows that the increase of building height (from 3m to 6m) increases the heating load (compared to scenario 9) due to the increase of building shade, which matches in the literature-review findings. That increase is very small (only 1.2%). The building façade, which is associated with albedo and material (Scenario 11 and 12), also has a very small effect on the heating load (no more than 2,4%).

Diagram 8.2 breaks down the heating load on 23rd June in each zone for the 12 site scenarios while Table 8.3 shows the heating load difference for each zone. This investigates how microclimate data in different direction influences heating load calculation in each zone (addressed in Section 8.1). Each scenario is similar as the biggest heating load is in the South zone, followed by the West zone. The North zone has the smallest heating load in every scenario, except in scenario 2 (Full pavement).

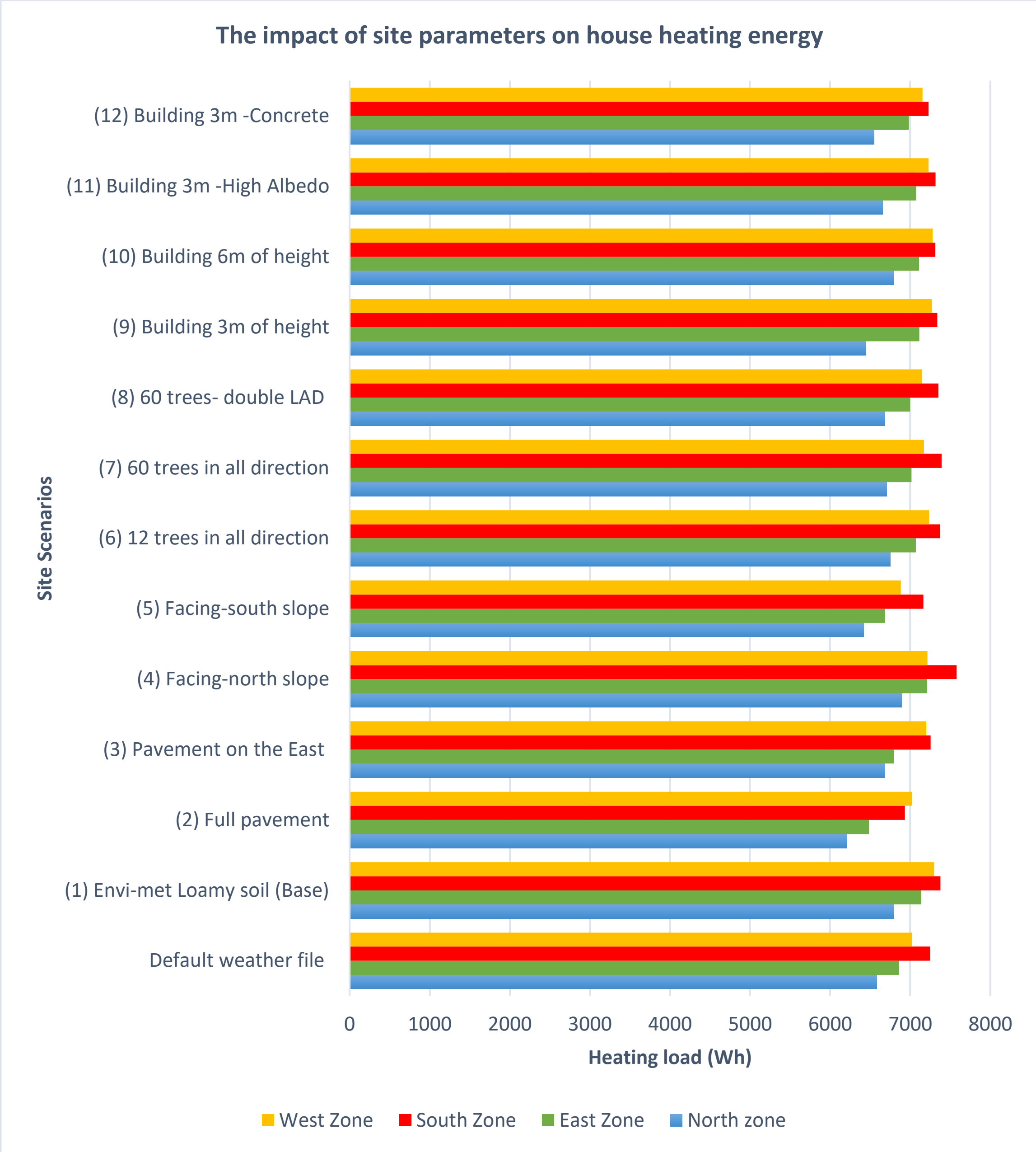


Diagram 8.2. Heating load in each zone tested

In the model using default weather file (default model), the heating-load difference for the East, south and west zone are 4%, 10% and 7% respectively compared to the North zone (see Table 8.3). This trend is generally like that of other site-parameter models with the difference no more than 5% in each zone, except Scenario 2 (full pavement) and Scenario 9 (buildings 3m of height).

In Scenario 2, the difference between the north and west zone increases to 13% compared to the default model. This difference is unexpected considering that ground surface is pavement in all direction, which supposedly leads to the same impact on air-temperature change in all direction. Meanwhile, Scenario 3 which applied the pavement only on the east area has similar trend of temperature difference in each zone as the default model.

Scenario 9 has considerable difference between the north zone and others three zones which are more than 9%. This difference is because the heating load in the north zone is lower by 5% than that of the base model while other zones are no more than 1%. That difference indicates Scenario 9 with nearby building produced warmer outdoor temperature than the base model with unobstructed area. It also indicates that this model produces the impact of nearby building which are contrasted to the literature review findings. In this case, supposedly the building objects in Scenario 9 can lead to cooler outdoor temperature due to its shading effect during the daytime.

	Difference (compared to North Zone)			
	North zone	East Zone	South Zone	West Zone
Default weather file	Base	4%	10%	7%
(1) ENVI-met Loamy soil (Base)	Base	5%	9%	7%
(2) Full pavement	Base	4%	12%	13%
(3) Pavement on the East	Base	2%	9%	8%
(4) Facing-north slope	Base	5%	10%	5%
(5) Facing-south slope	Base	4%	12%	7%
(6) Tree- One row	Base	5%	9%	7%
(7) Tree- Three rows	Base	5%	10%	7%
(8) Tree- Three rows double LAD	Base	5%	10%	7%
(9) Building 3m of height	Base	10%	14%	13%
(10) Building 6m of height	Base	5%	8%	7%
(11) Building 3m -High Albedo	Base	6%	10%	9%
(12) Building 3m -Concrete	Base	7%	10%	9%

Table 8.3. Heating load difference of each zone

These results show that among all site scenarios tested, only scenarios 2 and 4 produce large differences (-6.9% and -2.4% respectively) while only two scenarios (2&3) demonstrate the results matching to the literature-review findings. In this case, the simulation demonstrated the heating effect resulting from the pavement as the ground surface can reduce heating consumption. Other site parameters produce the contrary results against the literature review, but not very large (the difference is no more than 2.4%). The heating-load difference between four zones in the default model is generally like other 12 models using microclimate data from different direction.

8.7. Analysis

This section analyses the simulated output from ENVI-met site scenarios in relation to the results of house heating energy modelling in EnergyPlus. Although insignificant differences for heating load were found in section 8.6 for vegetation and nearby buildings, their simulated data should be analysed to ensure whether they influence the microclimate data in the model. As discussed in section 7.3.3, the air temperature difference by 1°C from midnight to 8am has a significant influence on heating load in simulation, while such a difference is not important around midday. In this case, there is a possibility that the tree or nearby building produces the air temperature change in ENVI-met, but the impact is not important in EnergyPlus model.

8.7.1. Ground surface

Diagram 8.3-8.6 compares the simulated hourly air temperature on 23rd June between the loamy soil (1), the full pavement scenario (2) and the pavement on the east (3). Overall, the full pavement model (2) has higher hourly air temperature than the loamy soil for the whole day by 1°C on average. This trend matches in the findings from section 7.4.2, based on the analysis results by Bowler, et al. (2010) and an additional test (see Diagram 7.63), where the dark pavement model using Kelburn weather produced warmer temperature of 0.9°C than the loamy soil model for 5th June 2016. The smallest difference emerges in the receptor 3 (south direction) where it has higher temperature by 0.7°C on average.

Meanwhile, the pavement on the east (3) produces cooler temperature than the full pavement (2) by 0.5°C on average in the east direction (receptor a2) and 0.9°C in other directions, which lead to 2.4% of heating load reduction. This difference suggests that the heating effect of pavement on house heating load can be significant if the house is surrounded by the pavement from all direction within the area of, at least, 50mx50m.

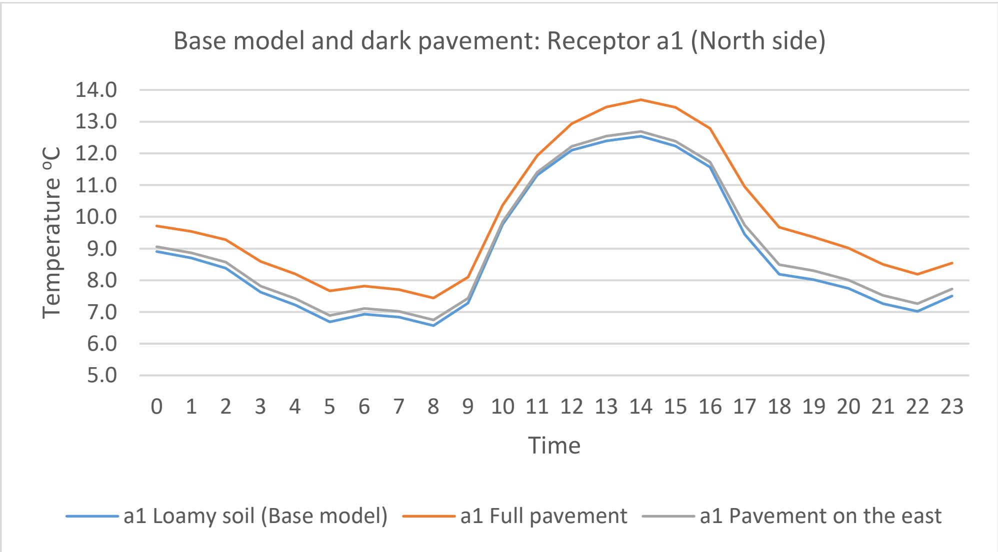


Diagram 8.3. Hourly air temperature between Base model and pavement scenarios –Receptor a1 (North)

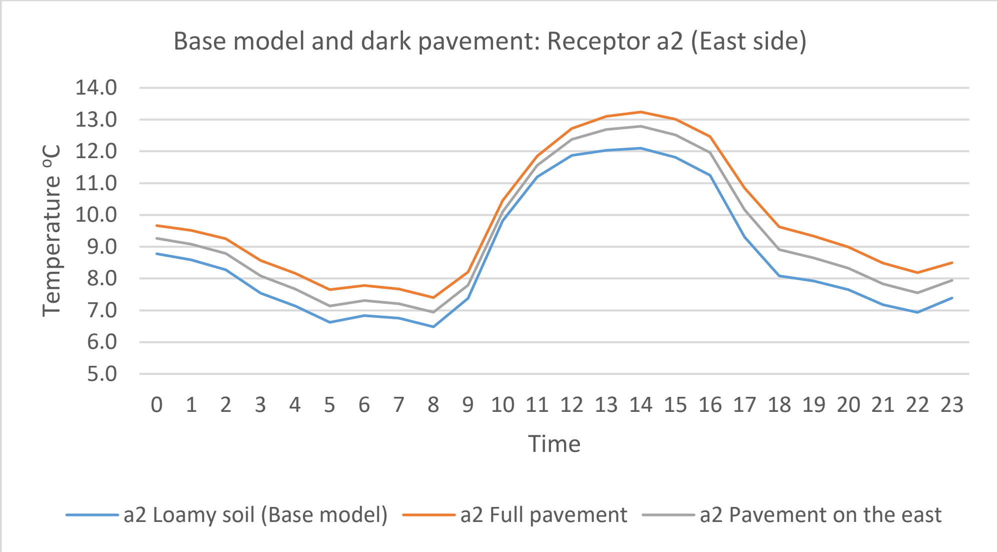


Diagram 8.4. Hourly air temperature between Base model and pavement scenarios –Receptor a2 (East)

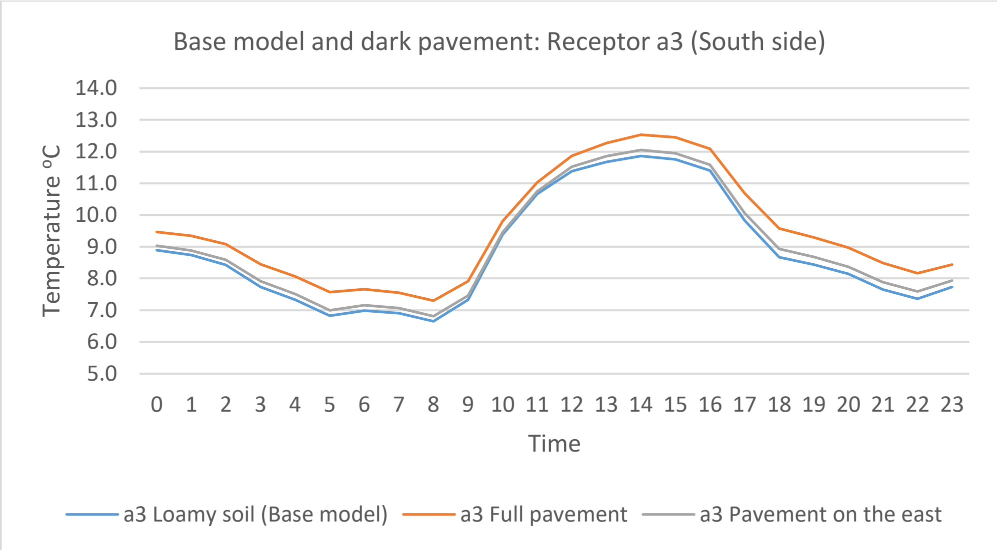


Diagram 8.5. Hourly air temperature between Base model and pavement scenarios –Receptor a3 (South)

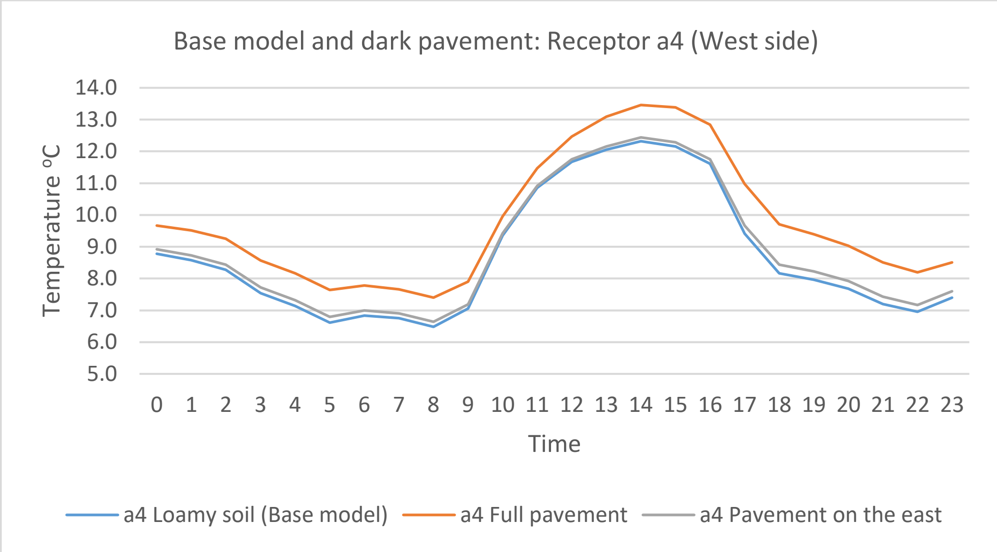


Diagram 8.6. Hourly air temperature between Base model and pavement scenarios –Receptor a4 (West)

The warmer temperature, averaging 1°C leads heating-load reduction by 6.9% in the full pavement model. Similar findings were also found in section 7.3.3 where the cooler temperature by averagely 1°C in ENVI-met model leads to the heating load increase by 9.6% (see Diagram 7.14 and Table 7.4). However, the analysis from section 7.3.3 highlighted that such a heating-load increase is due to air temperature difference from the midnight to 8am while temperature difference by up to 1°C during the day time has no effect on house heating load in the model.

Diagram 8.7 compares the hourly heating load of the base model and pavement scenarios on 23rd June. In general, those models do not use the energy for space heating from 11am to 6pm. This trend is matched in finding which was highlighted from 7.3.3, showing that during the daytime, the house model keeps above 18°C)by utilizing passive heating from solar radiation.

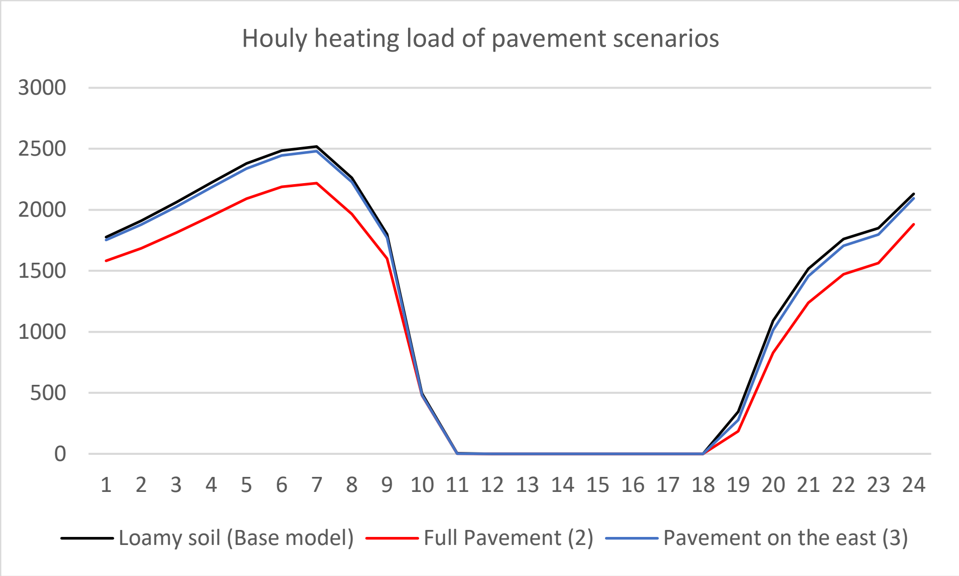


Diagram 8.7. Hourly heating load of pavement scenarios

8.7.2. Slope

Diagram 8.8-8.11 compare the simulated temperature data for the base model, facing-north and facing-south slopes scenarios. Overall, both base model and facing-north slope have similar temperatures, whereas the facing-south slope experiences significantly different trends.

Compared to the base model, the facing-north slope has lower temperatures after midday (15.00-23.00) in the north, east and south direction, which has the biggest difference compared to the base model in the south side (receptor a3), averaging 0.7°C in that time. The facing-south slope has lower air temperatures during the day (10am-3pm), averaging 1°C lower. It is warmer during the dark hours (dawn and night) by about 1°C in almost all directions. Interestingly, those three models have similar average air temperatures for the whole day between 8.7-9.1°C in all directions.

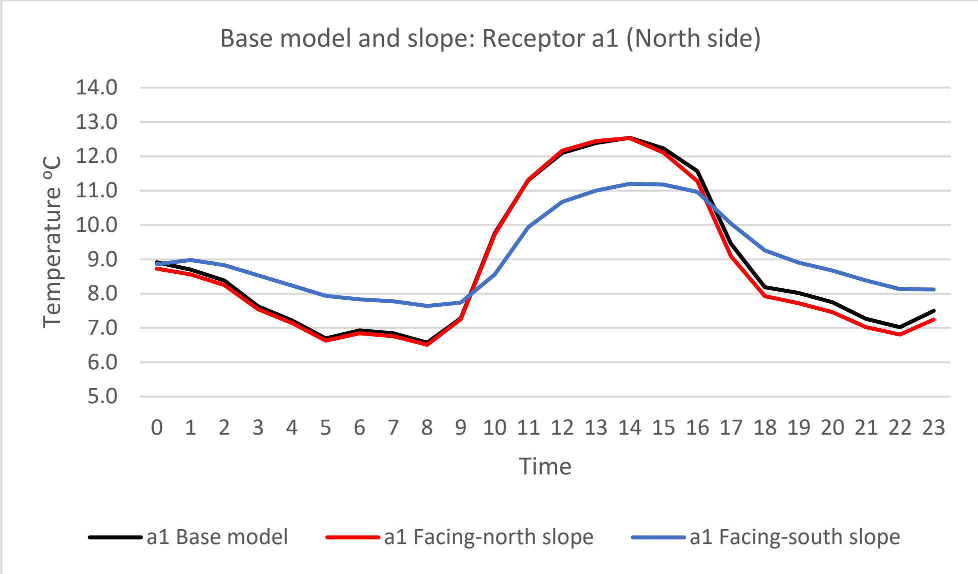


Diagram 8.8. Hourly air temperature between Base model and slope scenarios –Receptor a1 (North)

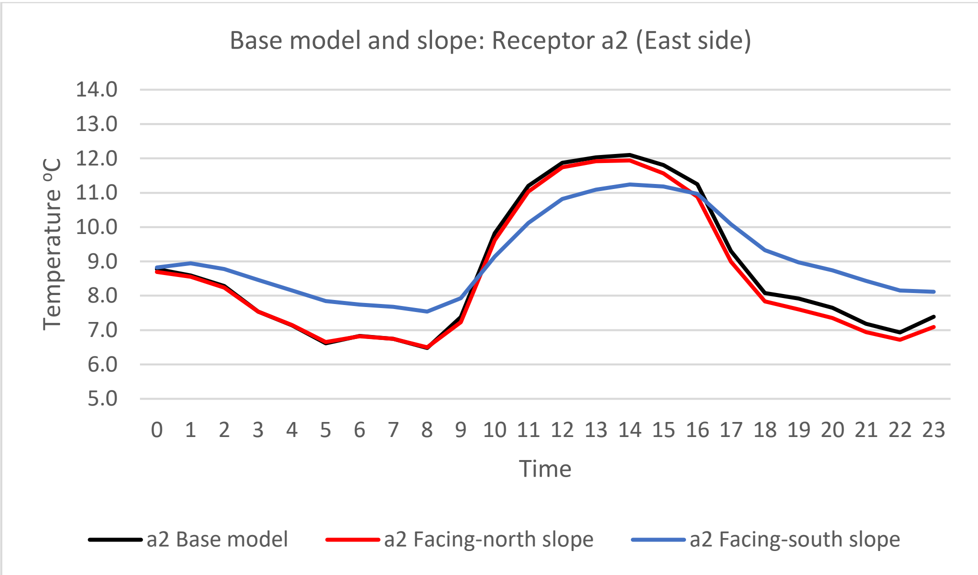


Diagram 8.9. Hourly air temperature between Base model and slope scenarios –Receptor a2 (East)

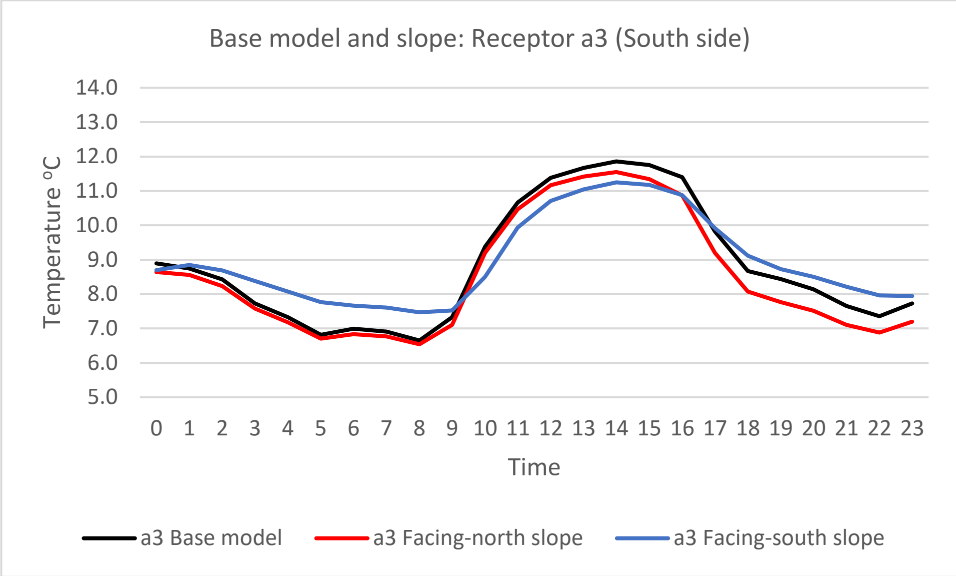


Diagram 8.10. Hourly air temperature between Base model and slope scenarios –Receptor a3 (South)

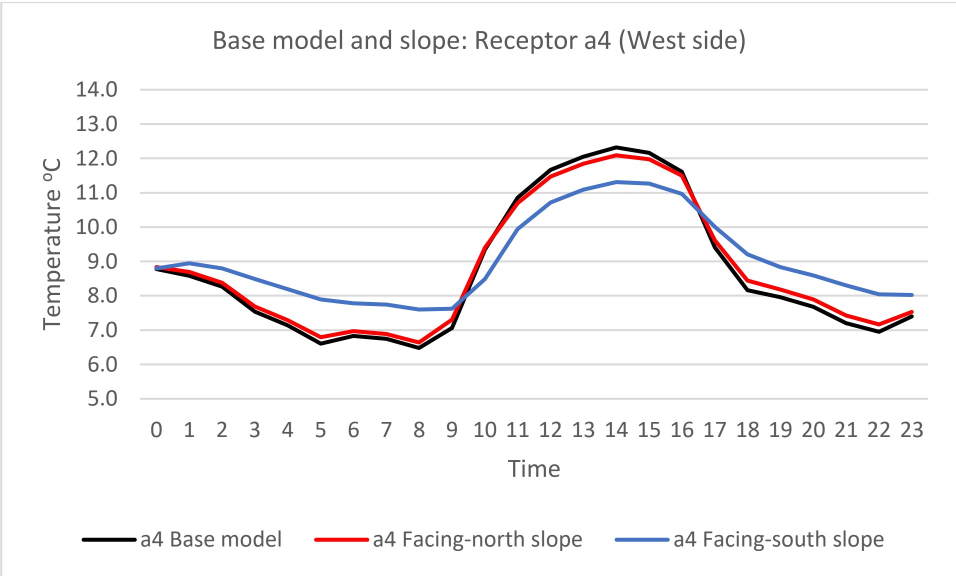


Diagram 8.11. Hourly air temperature between Base model and slope scenarios –Receptor a4 (West)

The Diagram 8.12 compares the hourly heating load of the base model and slope scenarios on 23rd June. Those models do not use the energy for space heating from 11am to 6pm. This trend is similar to that from the pavement scenarios in section 8.7.1, which suggests that the house model does not require active heating during the daytime.

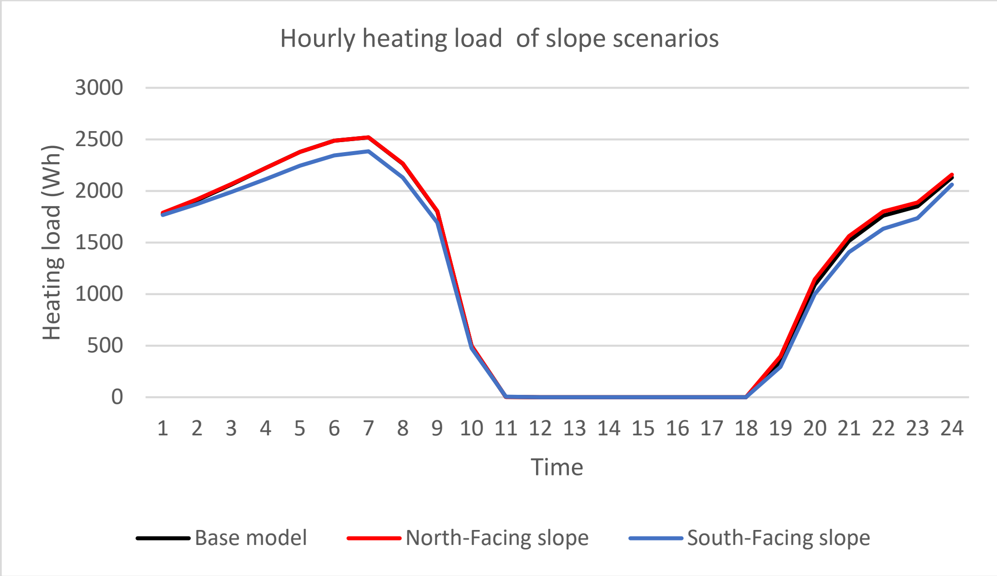


Diagram 8.12. Hourly heating load of slope scenarios

The hourly data of air temperature and heating load for the slope scenarios (Diagram 8.8-Diagram 8.11) explain the unexpected results in energy modelling:

- **The facing-north slope** generates cooler outdoor temperatures than the base model by 0.2°C on average from 4pm to midnight in north and east direction. Also, it has a much cooler temperature in the south direction in that time, averaging 0.6°C. As a result, it has higher heating consumption than the base model by only 1%.
- **The facing-south slope** generates warmer temperature during the dawn and night, averaging 1°C more than the base model, and this leads to 5% reduction of heating load. In addition, it is cooler than the base model during the midday by about 1°C, but it does not influence the heating load during the daytime. This is because the house model can maintain the indoor temperature by passive heating, which is also found the pavement model from section 8.7.1 and an additional test in from section 7.3.3.

Overall, in terms of microclimate modelling, those two slope scenarios generate unexpected results (not like literature-review findings). First, instead of increasing air temperature due to the surface inclination, the facing-north (equatorial) slope in ENVI-met model generates slightly cooler temperature in three direction (north, east and south) after midday until midnight. Secondly, the facing-south slope produces much warmer temperature during the dark hours (dawn and night). However, it produces realistic results around midday, where the air temperature is much cooler due to the facing-south slope blocking the solar radiation.

8.7.3. Vegetation –The number of tree and leaf densities

Diagram 8.13-8.16 show the simulated data between the base model and one-row tree model (scenario 6). In general, the one-row model (12 trees in all direction) has slightly higher air temperature than the base model during the daytime (10.00-16.00). The most air-temperature increase occurs in south and west directions (receptors a3 and a4), which are higher than the base model by about 0.3ºC.

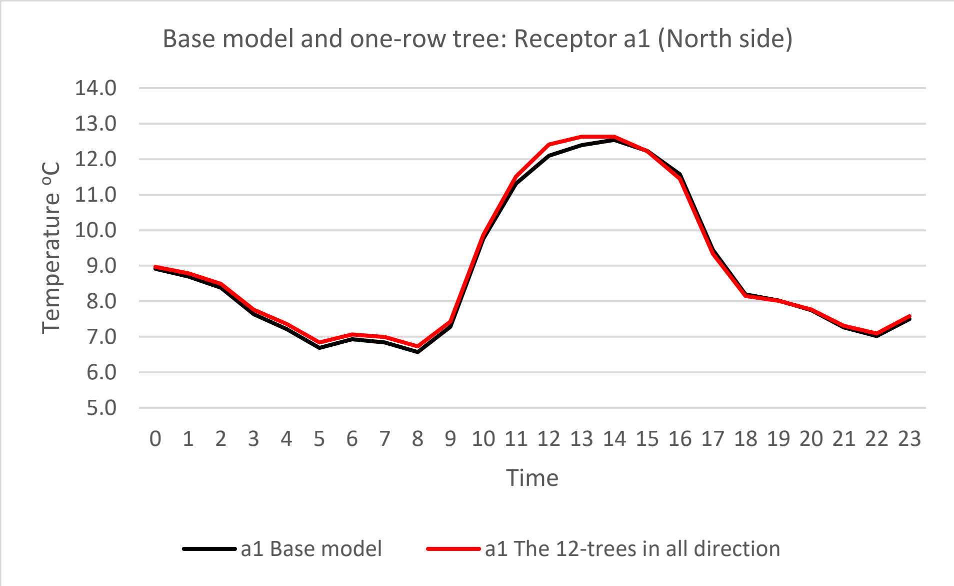


Diagram 8.13. Hourly air temperature between Base model and one-row tree scenario –Receptor a1 (North)

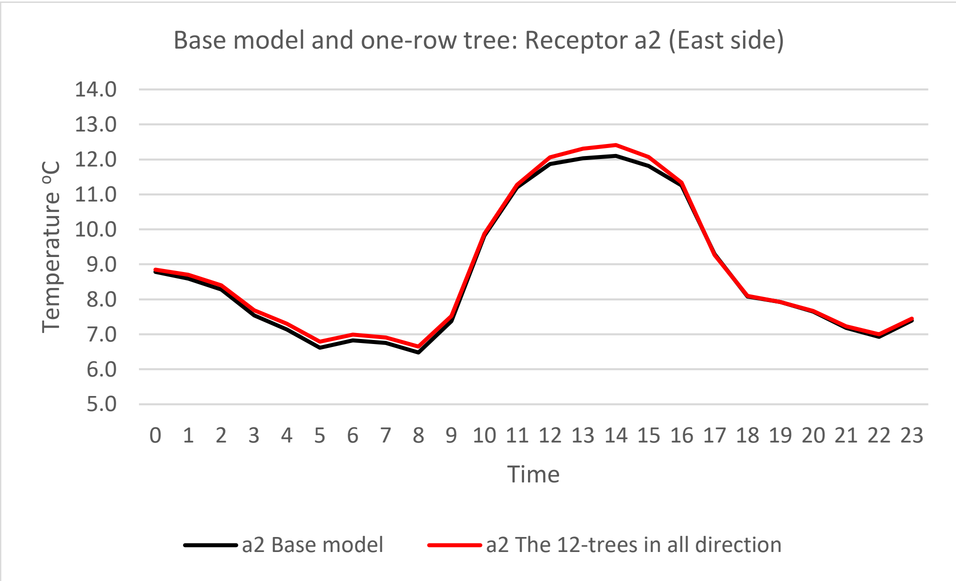


Diagram 8.14. Hourly air temperature between Base model and one-row tree scenario –Receptor a2 (East)

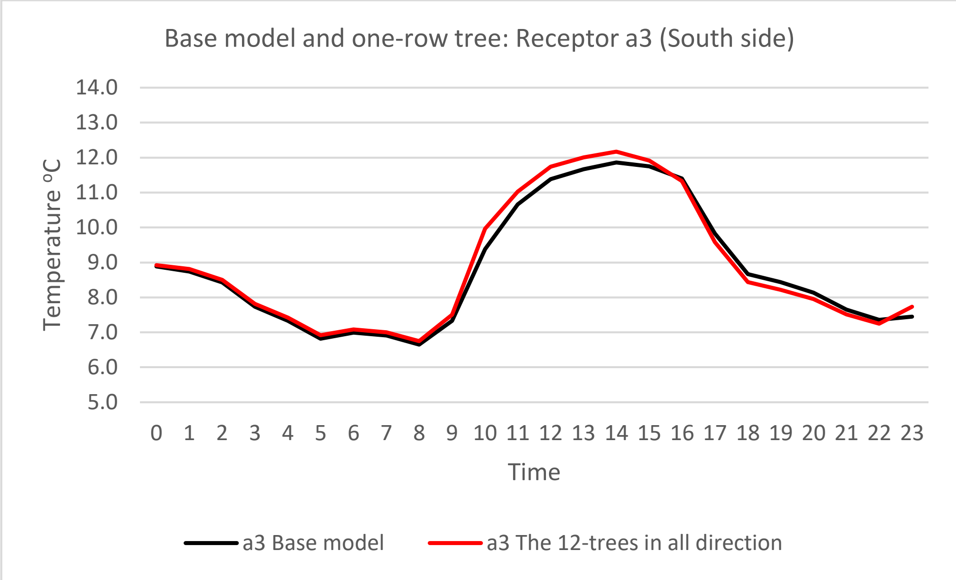


Diagram 8.15. Hourly air temperature between Base model and one-row tree scenario –Receptor a3 (South)

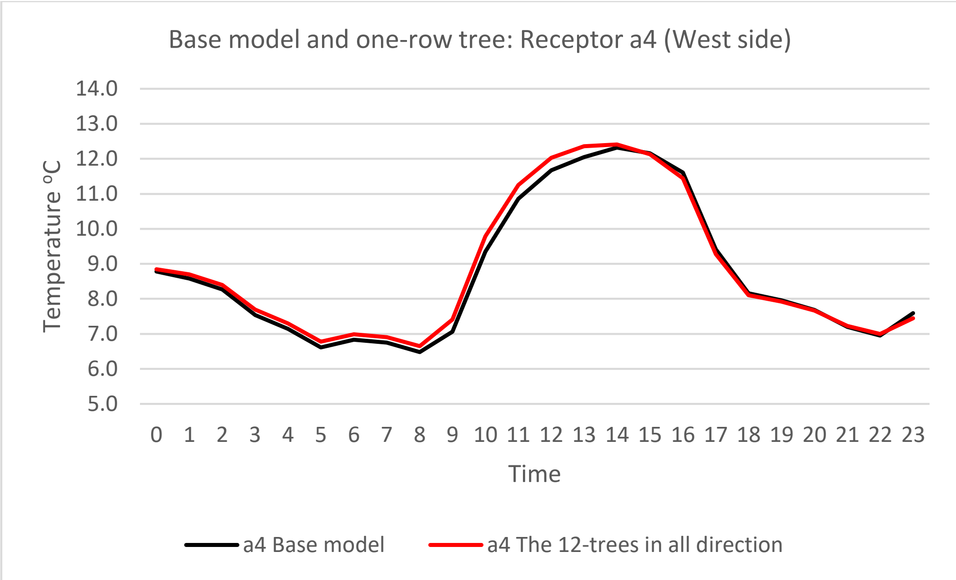


Diagram 8.16. Hourly air temperature between Base model and one-row tree scenario –Receptor a4 (West)

Diagram 8.17-8.20 compares the simulated data of all the tree models (scenario 6, 7 and 8). In general, those three models produce similar results of microclimate data. In addition, the three-rows tree model with double LAD (Scenario 8) has a slightly warmer hourly air temperature than other tree models by 0.1°C on average.

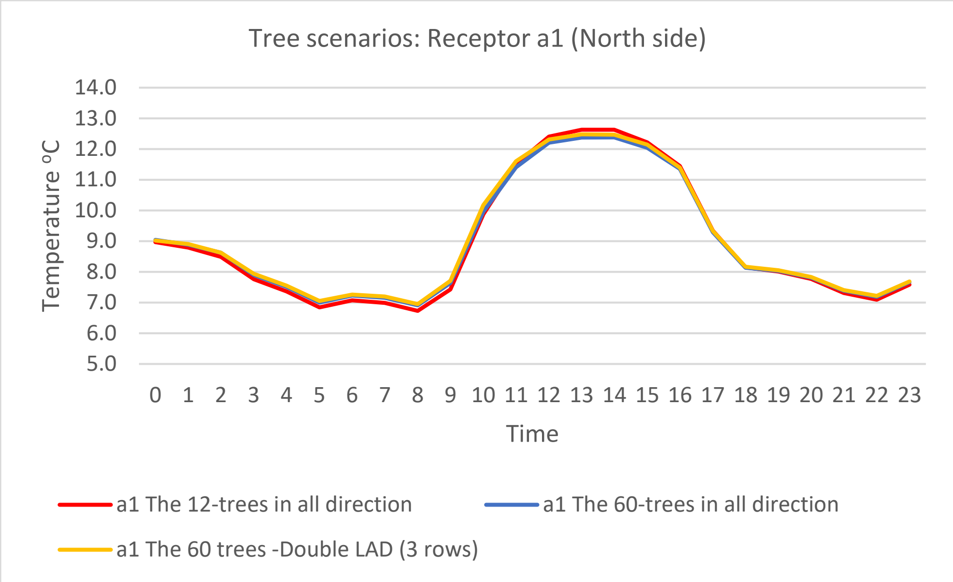


Diagram 8.17. Hourly air temperature of all three scenarios of tree –Receptor a1 (North)

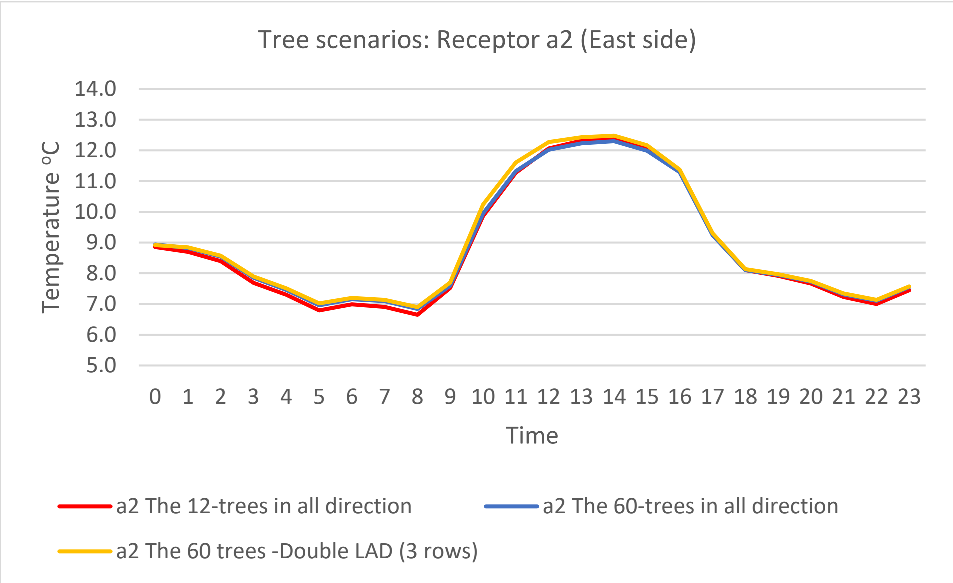


Diagram 8.18. Hourly air temperature of all three scenarios of tree –Receptor a2 (East)

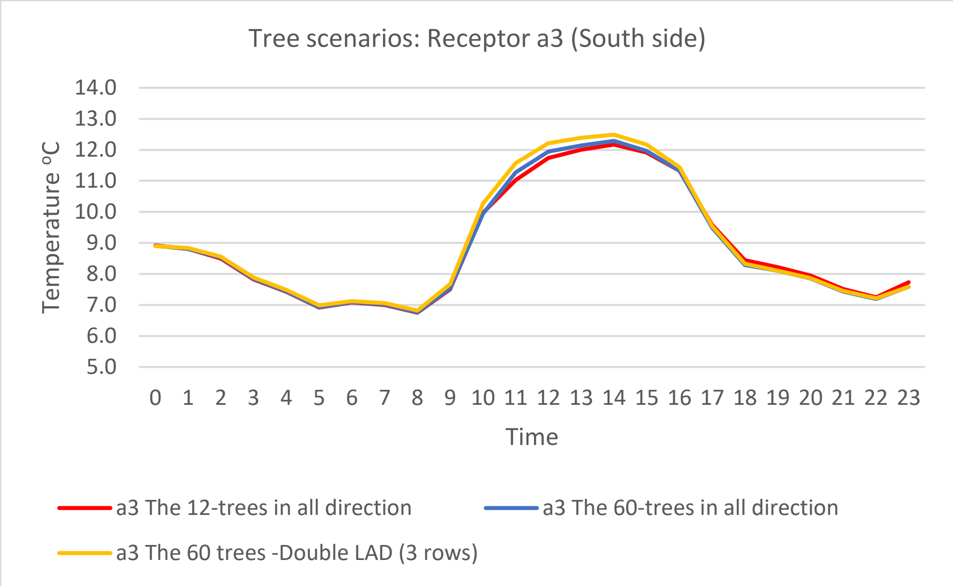


Diagram 8.19. Hourly air temperature of all three scenarios of the tree –Receptor a3 (South)

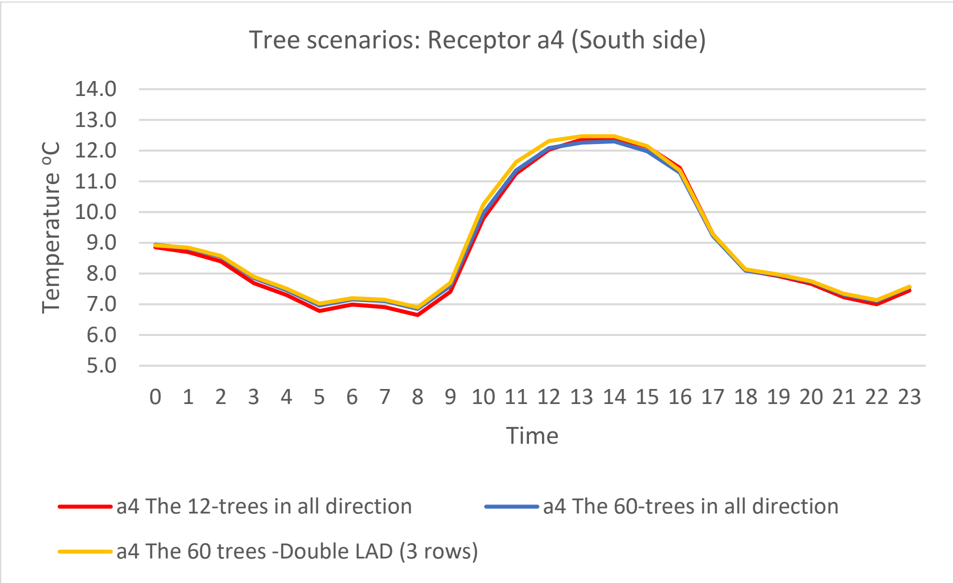


Diagram 8.20. Hourly air temperature of all three scenarios of the tree –Receptor a4 (West)

Based on the literature review, it is expected that the tree model can reduce the surrounding outdoor air temperature due to its shade and evaporation effect. However, as can be seen in Diagram 8.13-8.16, the 12-trees model experiences warmer temperature than the base model during the daytime. The increase of tree numbers (scenario 7) and Leaf Area Density (LAD – Scenario 8) does not reduce the air temperature on the site significantly. Even the 60-trees with double LAD (scenario 8) has the highest air temperature during the midday compared to other tree scenarios.

The Figure 8.7 and 8.8 shows the graphic analysis of 2D air temperature above 1.5m from the ground for both tree scenarios (Scenario 6 and 7). The 2D analysis is performed through

LEONARDO, one of ENVI-met tools for extracting numerical output to 2D or 3D analysis. This analysis examines how the ENVI-met model behaves to the tree models in scenario 6 and 7. This aims to confirm the results of tree scenarios produced by receptors (diagram 8.13-8.20).

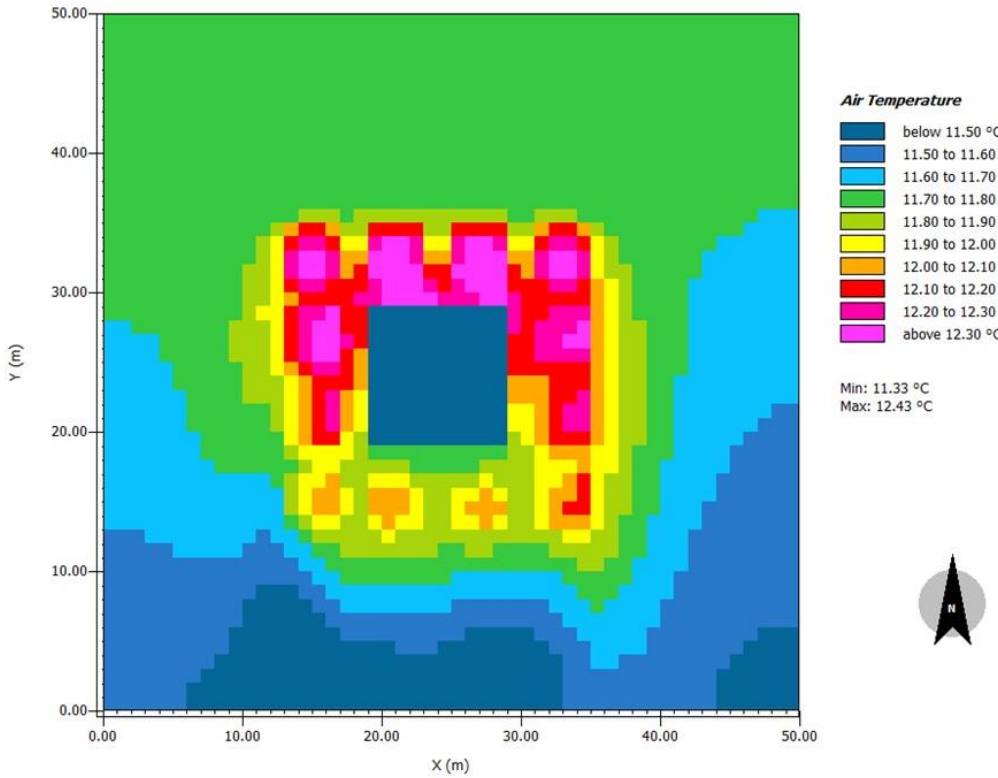


Figure 8.7. The 2D map of air temperature analysis for the 12-trees model at 12.00 on 23rd June (Scenario 6)

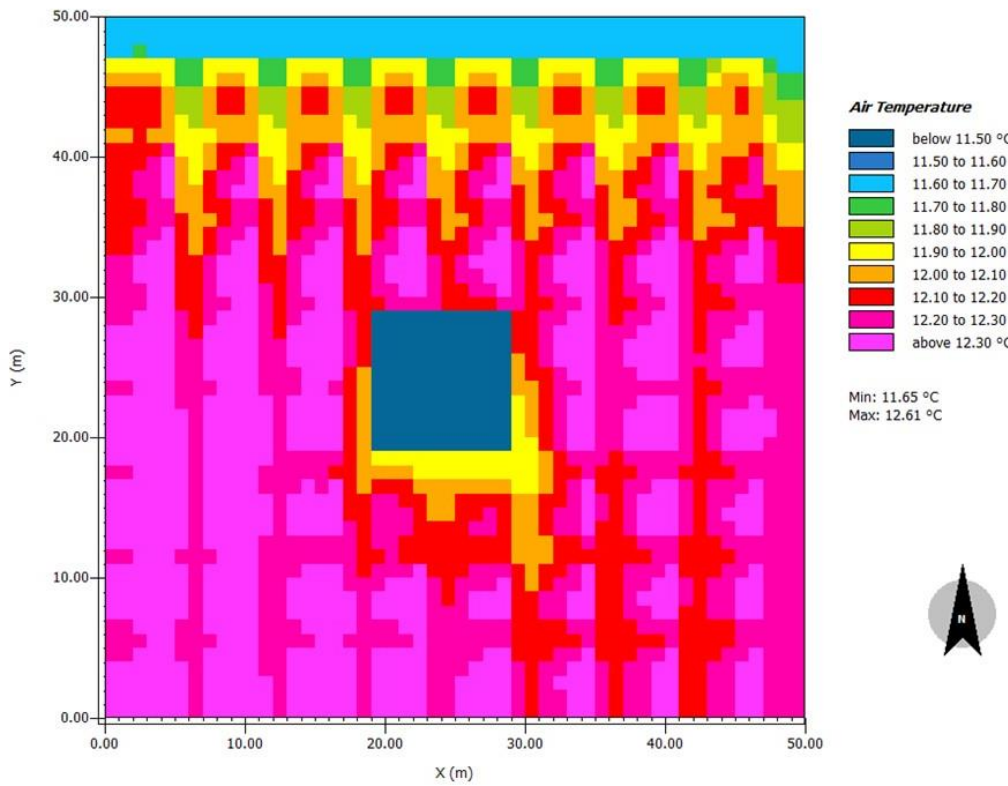


Figure 8.8. The 2D map of air temperature analysis for the 60-trees model at 12.00 on 23rd June (Scenario 6)

The 2D map of air temperature of both tree scenarios reveals that the air temperature below the tree in the model is slightly warmer than the open-flat area, by between 0.4 and 0.5°C. This confirms that the tree model in ENVI-met produces the impact which is contrary to the literature review findings –Instead of cooling the air temperature through its shade and evapotranspiration, the tree models warm the air temperature below.

From the simulated data (Diagram 8.13-8.20) and graphic analysis (Figure 8.7 and 8.8), it is concluded that all tree models in ENVI-met (scenario 6, 7 and 8) produce the output which is not like the literature review findings, and this leads to unexpected results in the energy modelling.

8.7.4. Nearby buildings: Height and surface

Diagram 8.21-8.24 reveal the simulated data of hourly air temperature for the base model and nearby building scenarios (3m and 6m height). Overall, all those models have similar results in the east, south and west direction while there is a difference in the north direction.

In the north direction (receptor a1), the model with nearby buildings of 6m height has a lower temperature than the base model by about 0.5°C during the daytime (11.00-15.00). The 3m-height temperature is slightly lower than the base model during the day but is higher by 0.5°C in the evening. Meanwhile, the temperatures from both the 3m and 6m buildings are higher in the south direction than the base model during the midday by about 0.2^{o}C.

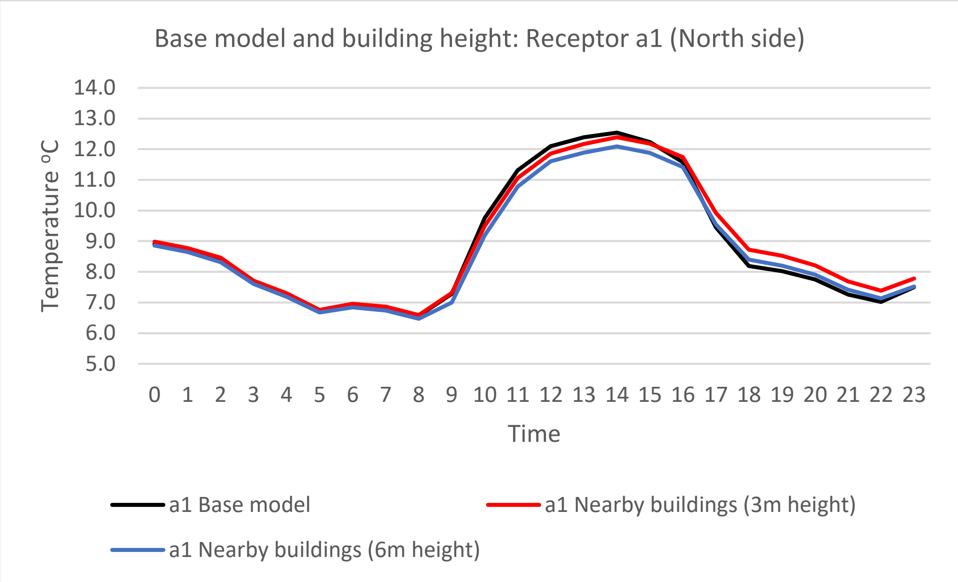


Diagram 8.21. Hourly air temperature of nearby building scenarios –Receptor a1 (North)

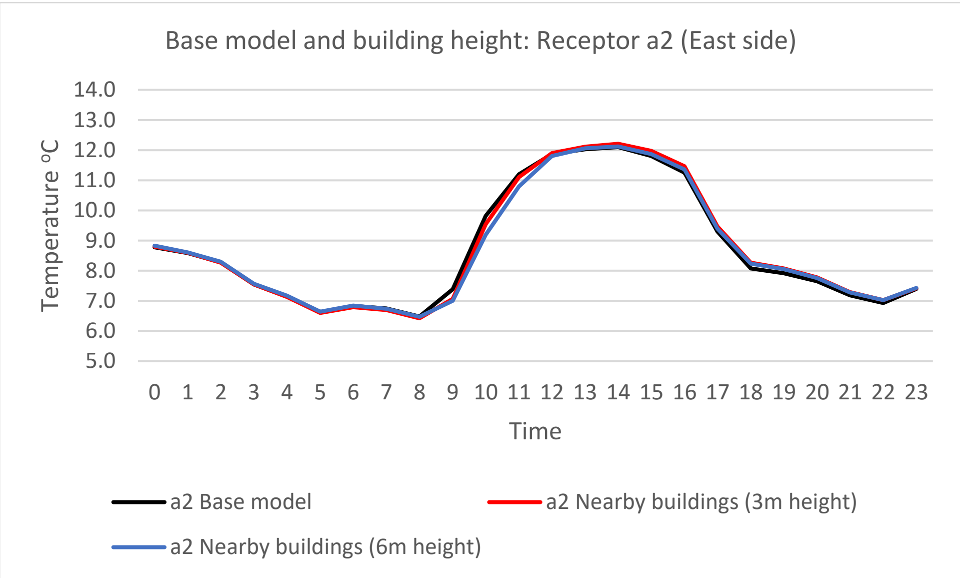


Diagram 8.22. Hourly air temperature of nearby building scenarios –Receptor a2 (East)

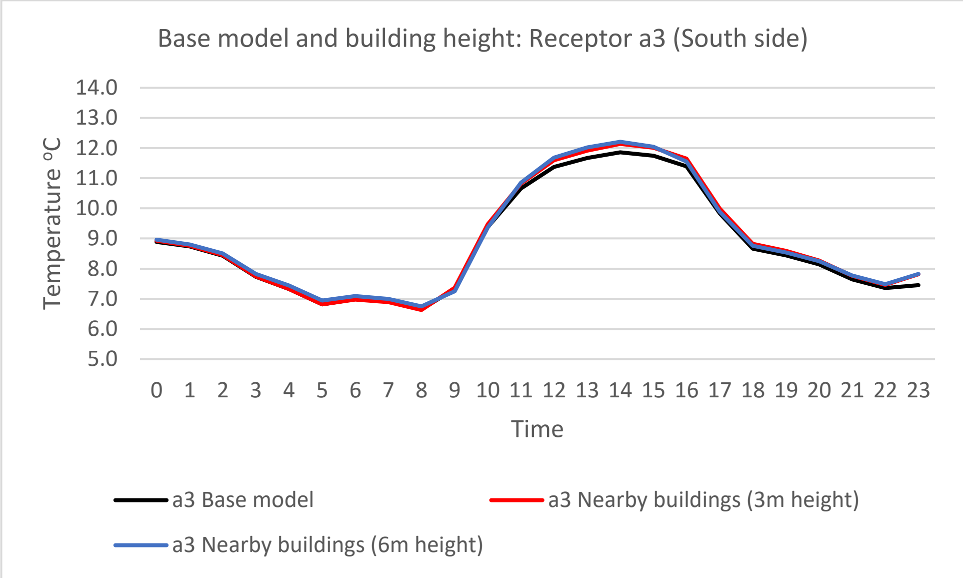


Diagram 8.23. Hourly air temperature of nearby building scenarios –Receptor a3 (South)

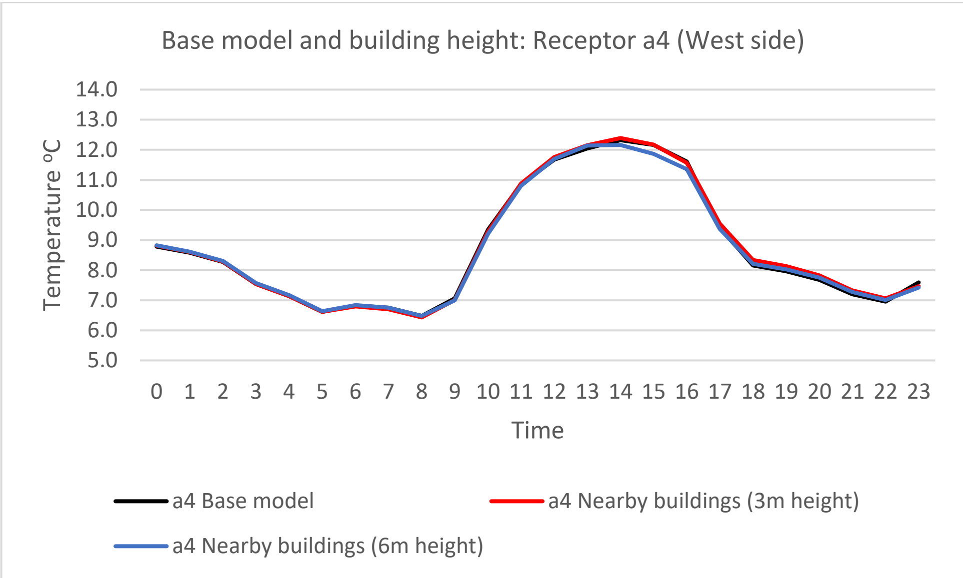


Diagram 8.24. Hourly air temperature of nearby building scenarios –Receptor a4 (West)

Diagram 8.25-8.28 compares the temperature data from the nearby building scenarios with different surface materials. Overall, they produce very small difference of no more than 0.2°C.

The model with concrete surfaces is slightly warmer in the dawn and evening compared to other surfaces by 0.2°C on average. Meanwhile, the weatherboard surface has the highest temperature during the midday compared to others. The ENVI-met reflection value for weatherboard and high albedo surface are 0.4 and 0.7 respectively.

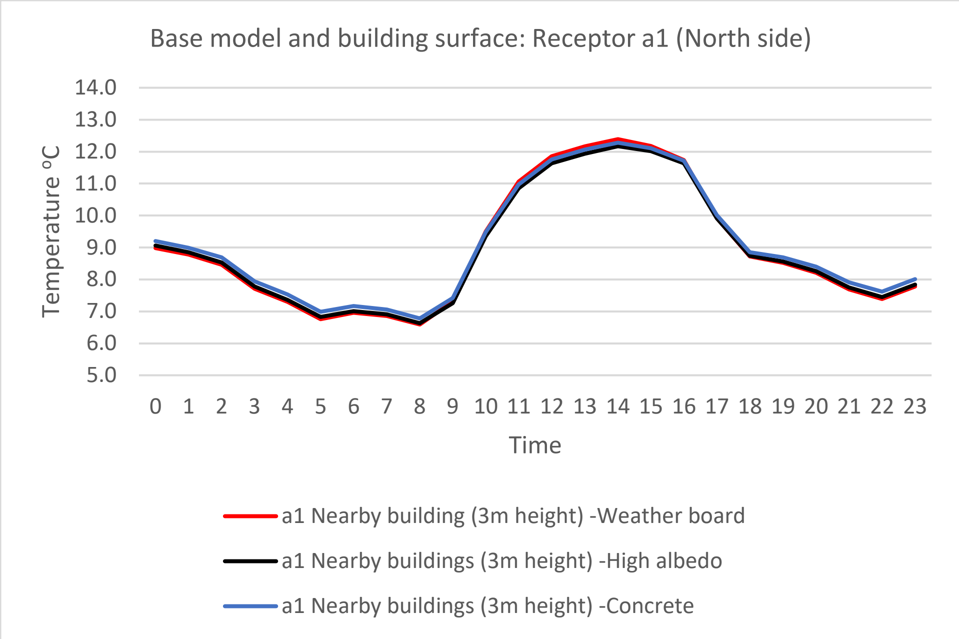


Diagram 8.25. Hourly air temperature of nearby building surface –Receptor a1 (North)

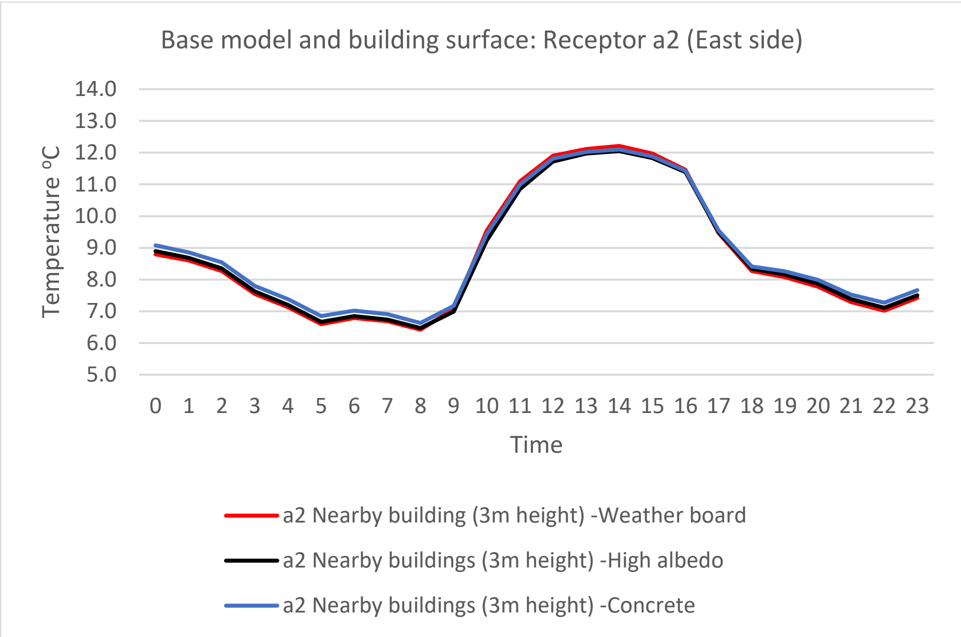


Diagram 8.26. Hourly air temperature of nearby building surface –Receptor a2 (East)

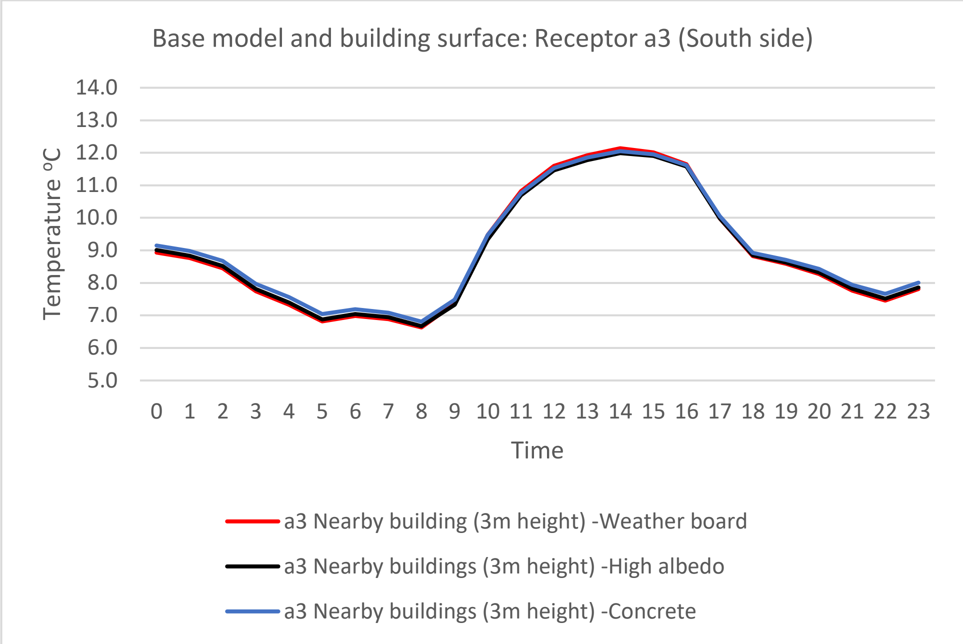


Diagram 8.27. Hourly air temperature of nearby building surface –Receptor a3 (South)

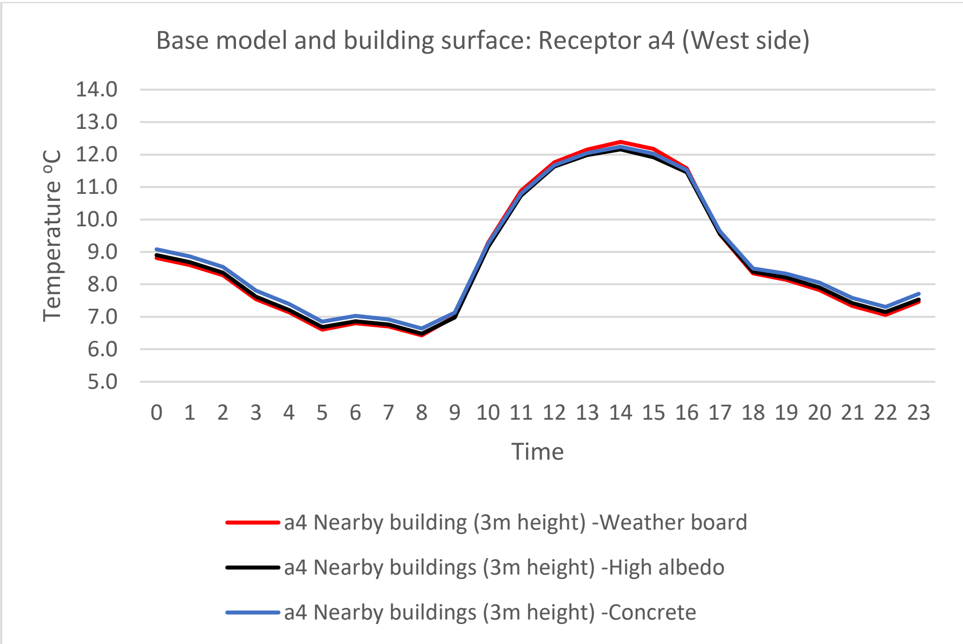


Diagram 8.28. Hourly air temperature of nearby building surface –Receptor a4 (West)

The simulated temperature data from Diagram 8.21-8.28 shows that the nearby building scenarios produce the sensible results:

- **building height.** The building height of 6m has lower air temperature compared to other models. This indicates that the solar radiation in the north side is blocked by nearby buildings located in the north side. The Diagram 8.23 shows that both nearby building models with 3m and 6m height have slightly higher air temperature in the south side than the base model (without building). This might indicate that the nearby building located in the south direction heats the air temperature through its façade.

- **The building surface material.** According to Diagram 8.25-8.28, the concrete material affects air temperature in the dawn and night. This indicates that thermal mass materials (such as concrete) release heat during the night. The lightweight weatherboard (lowest reflection value) generates the highest temperatures during the midday compared to other surfaces.

The nearby building models are likely to produce the realistic results which confirm the literature-review findings about the site impact. However, their impact on temperatures is very small, leading to the very small difference (less than 3%) of house heating energy compared to the base model (Table 8.2).

8.7.5. Overall summary

The analysis of simulated data for ground surface, slope, vegetation and nearby building explains the unexpected results from the parametric study of testing site impact. Overall, it can be summarised that:

1. The slope model in ENVI-met generates an impact that is different to the literature-review findings. The facing-north (equatorial) slope model does not warm up the ambient temperature due to its surface inclination while the facing-north slope increases significantly the ambient temperature in the model during the dark time (averaging 1^{o}C).
2. The tree model in ENVI-met produces contrary impact compared to the literature review findings. In this case, the tree models in ENVI-met warms the air temperature below instead of cooling the air temperature through its shade and evapotranspiration
3. The impact produced by nearby building models in ENVI-met might be in accordance with the literature-review findings, but their impact is insignificant.

8.7.6. Reflection

8.7.6.1. Unexpected impact of slope model

Through online ENVI-met forum, it was confirmed by one of the admins that vertical surface of slope model in ENVI-met does not interact with the microclimate system as it is only an artificial surface due to the grid structure (ENVI-met Forum, 2018). This confirmation explains why the facing-north (equatorial) slope does not warm up the ambient temperature in ENVI-met model.

Meanwhile, the facing-south slope heating up the ambient temperature during the night-time in ENVI-met model is still unexplained. There is no explanation yet from the literature review that slope surface can heat up the ambient temperature during the night, especially that which is not exposed to the sun during the day (Non equatorial facing). Thus, the unexpected impact of both slope models (facing north and south) means that ENVI-met has limitation in generating the slope impact on local microclimate.

8.7.6.2. Contrary impacts of trees

The simulation results of the tree scenarios are contradictive to not only the literature findings but also to the previous study using ENVI-met by Morakinyo, et al. (2016). That study found that tree model can reduce the outdoor air temperature in ENVI-met model and indoor air temperature in EnergyPlus model when they integrated it with ENVI-met.

There are two possibilities for these results. First, the previous study was in a warm humid region (Nigeria) where daytime ambient air temperature can be over 25ºC. That condition is contrasted to the climate of winter in Wellington where the air temperature ranges from 6-12ºC (NIWA, 2014). Thus, the tree model in ENVI-met is unlikely to cool the already cold ambient temperature. Second, there is a possibility that the tree model used in the parametric study is not proper or invalid. This was also found in the ground-surface impact testing (7.4.2) where the asphalt surface in ENVI-met does not produce the impact like literature review findings, but pavement does. Thus, it is suggested to conduct an additional test of tree models, which use a different tree model from ENVI-met database, to see whether it can produce the impact which is like the literature-review findings -The additional test is discussed in section 8.8.

8.7.6.3. Insignificant impact of nearby buildings

The simulation results from the nearby-buildings scenarios produce a very small impact on the air temperature change, which leads to an insignificant impact on the heating energy. In this case, the nearby-buildings scenarios tested the site with the low-buildings environment – with a maximum building height of 6m.

However, a study by Middel, et al. (2014) revealed that the nearby buildings, in the urban context, create local cool island due to shade where the buildings are tall and dense. This study used ENVI-met (Version 3.1) to measure the impact of urban form or building configuration on the microclimate, and its simulation results show that the building of 9m height reduces the air temperature by 2ºC (above 2m from the ground) in the central courtyard. That study case was in the Phoenix-Arizona, which is in a semi-arid climate where the summer air temperature reaches about 45°C . In other words, the building shade has a big influence in cooling the air temperature in hot climatic conditions but not necessarily in the cold climate of winter in Wellington and the height of building models which are relatively short (only 3m and 6m tested).

8.8. Additional testing for the impact of tree model

The additional testing uses a tree model, which is different from that in the parametric study. This aims to see whether another tree model produces an impact which is like the literature review findings.

In general, there are two types of tree model in ENVI-met database: simple plant and 3D plant. The difference is that the simple plant model can be simply modelled in each grid cell while the 3D plant is one unit of a particular tree, which consists of a particular configuration of grid cells. Figure 8.9 illustrates both the simple plant and 3D plant in ENVI-met model.

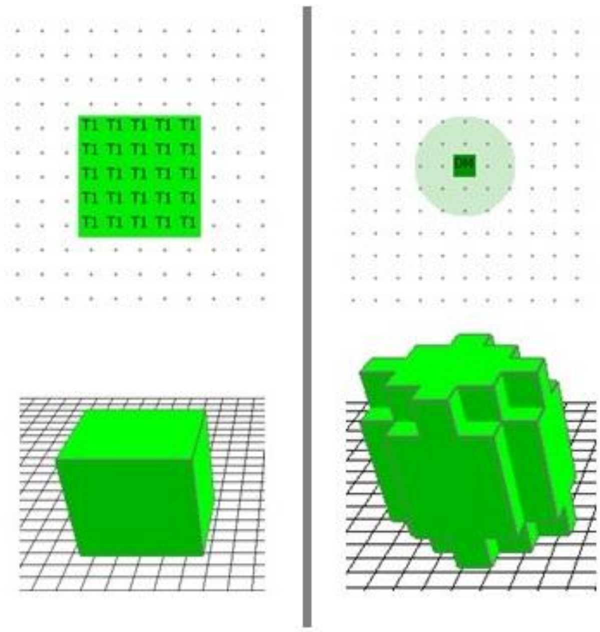


Figure 8.9. Simple plant (left) and 3D plant (Right)

This test applies conifer tree "[01ALDM] conic, large trunk, dense, medium", which has 15m of height and high LAD. Two scenarios were tested: (1) the 12-conifers and (2) the 32 conifers scenarios, as depicted in Figure 8.10.

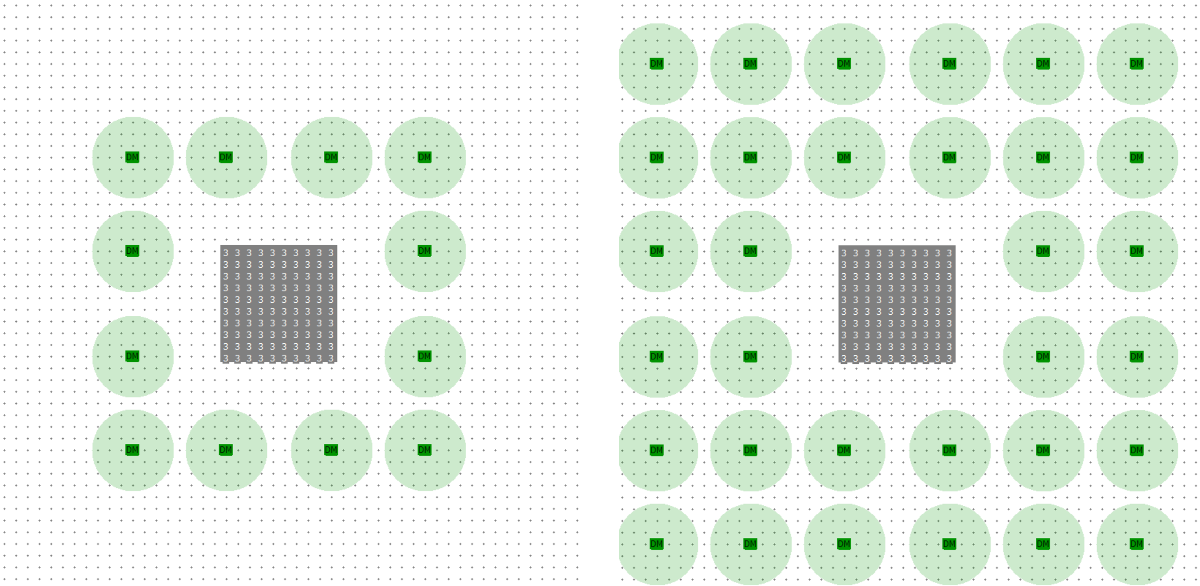


Figure 8.10. The 12-conifers (left) and the 32-conifers (Right) scenarios

The four following diagrams (8.29-8.32) compare the simulation results of conifer-trees scenario with the base model. Overall, both conifer-trees scenarios experience the slight increase of air temperature during the dark hours, especially in the dawn and morning (from 00.00-08.00). In the north and south directions (receptor a1 and a3), the 32-conifers model has slightly lower air temperature than the base model, which is by about 0.3ºC whereas the 12-conifers model is slightly higher than the base model. Meanwhile, all models relatively have same the value of hourly air temperature in the east and west directions during the midday and afternoon.

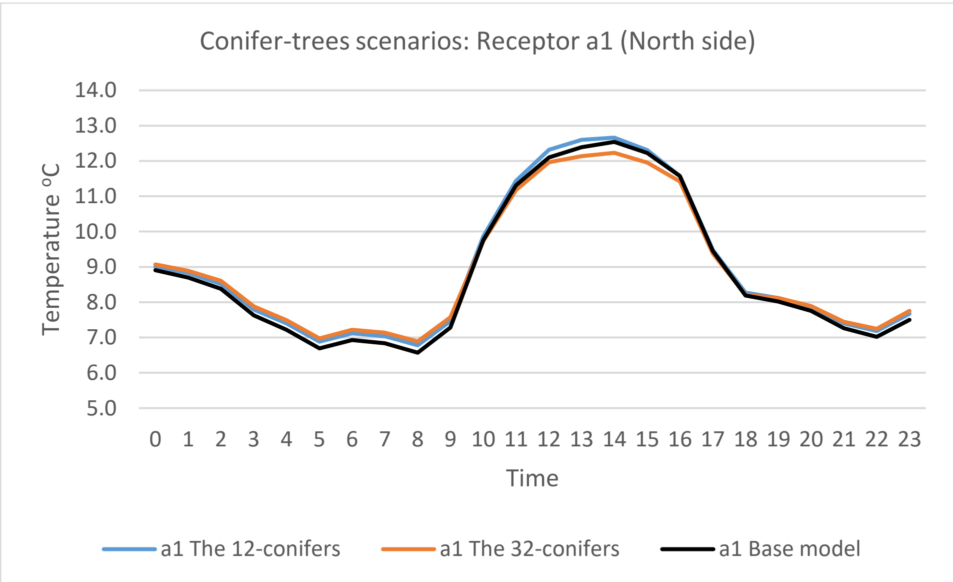


Diagram 8.29. Hourly air temperature of all three scenarios of the tree –Receptor a1 (North)

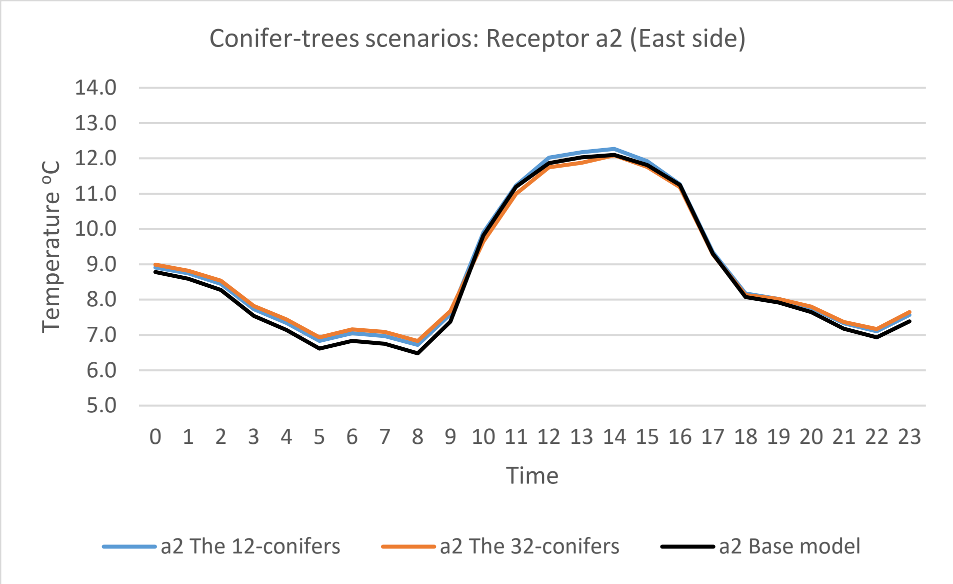


Diagram 8.30. Hourly air temperature of all three scenarios of the tree –Receptor a2 (East)

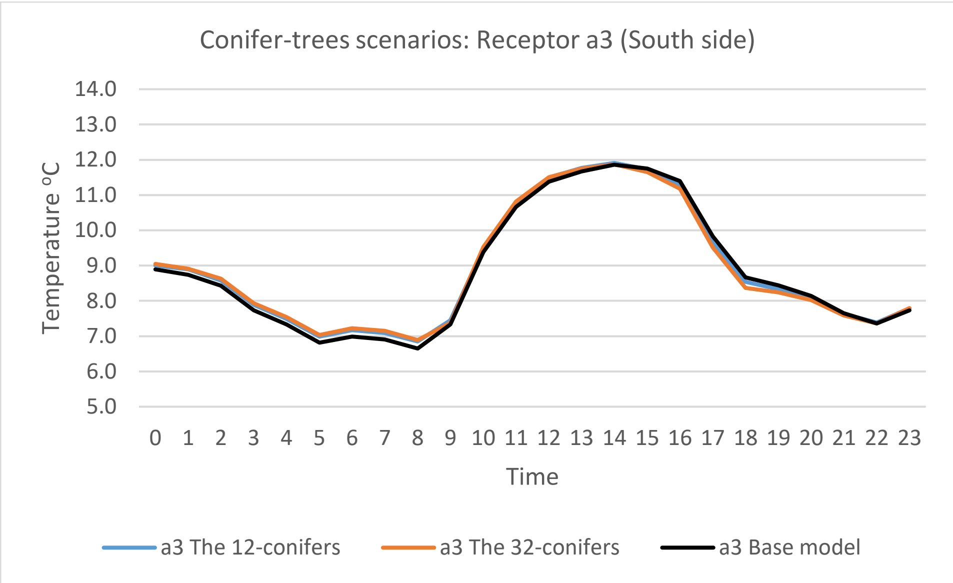


Diagram 8.31. Hourly air temperature of all three scenarios of the tree –Receptor a3 (South)

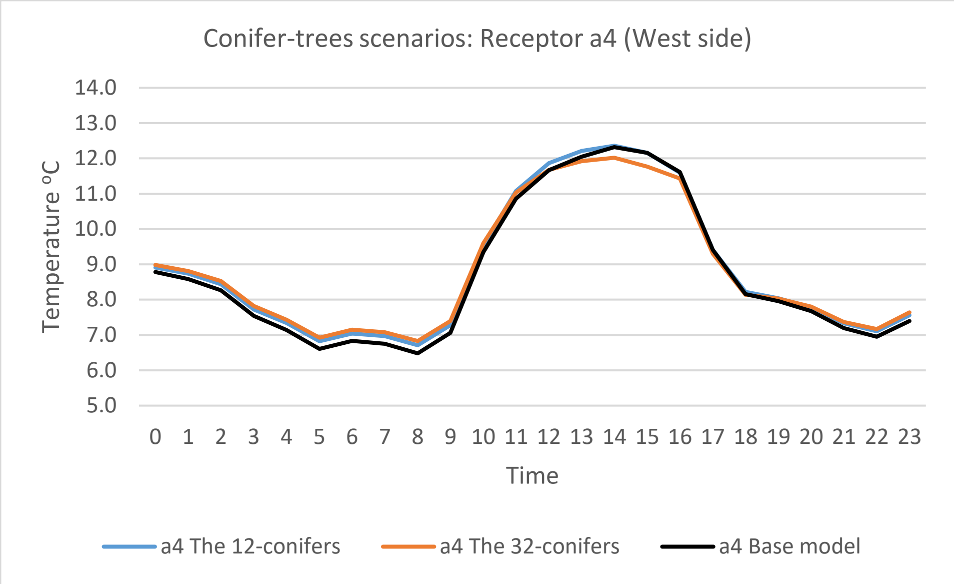


Diagram 8.32. Hourly air temperature of all three scenarios of the tree –Receptor a4 (West)

The simulated data indicates that the conifer-tree models also produce inconsistent results compared to the base model. The 32-conifers model shows the reduction of air temperature during the midday compared to the base model, but the 12-conifers model does not experience this reduction. Instead of cooling the air temperature, the 12-conifers model slightly increases the air temperature during the midday by about 0.1^{o}C.

Figure 8.11, 8.12 and 8.13 provide graphic analysis of 2D air temperature above 1.5m from the ground for the base model and both conifer-trees models at 12.00 on 23rd June. Both conifer-trees models produce warmer temperature (surrounding the building) than the base model.

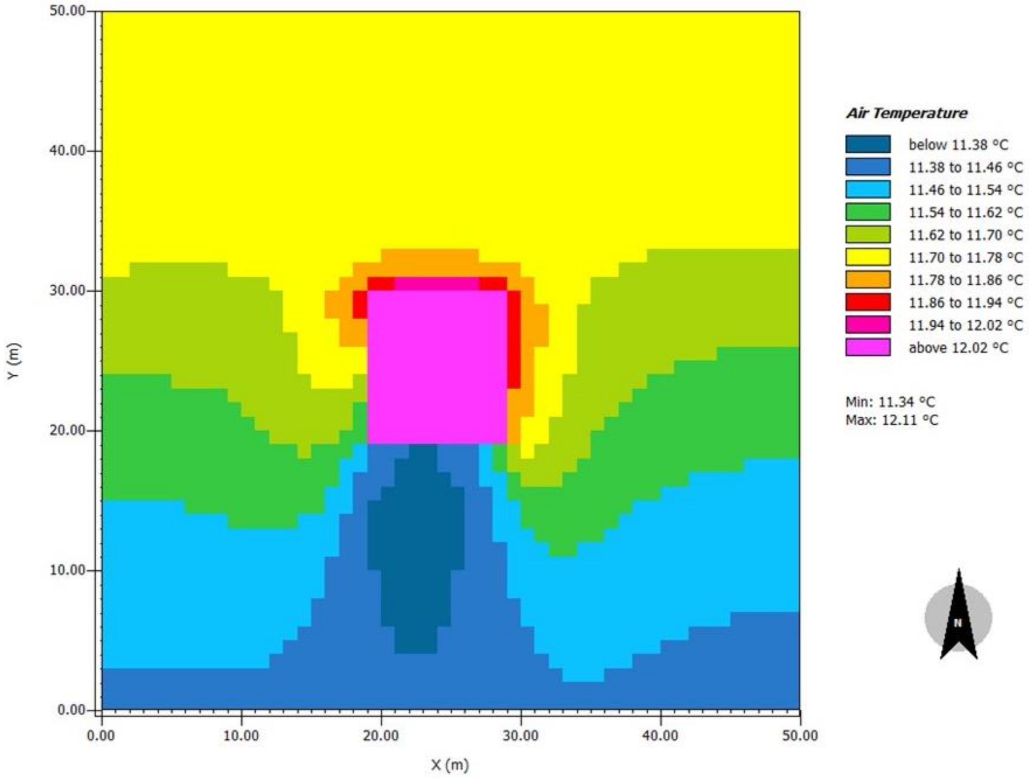


Figure 8.11. The 2D map of air temperature analysis for the Base model (open-flat) at 12.00 on 23rd June

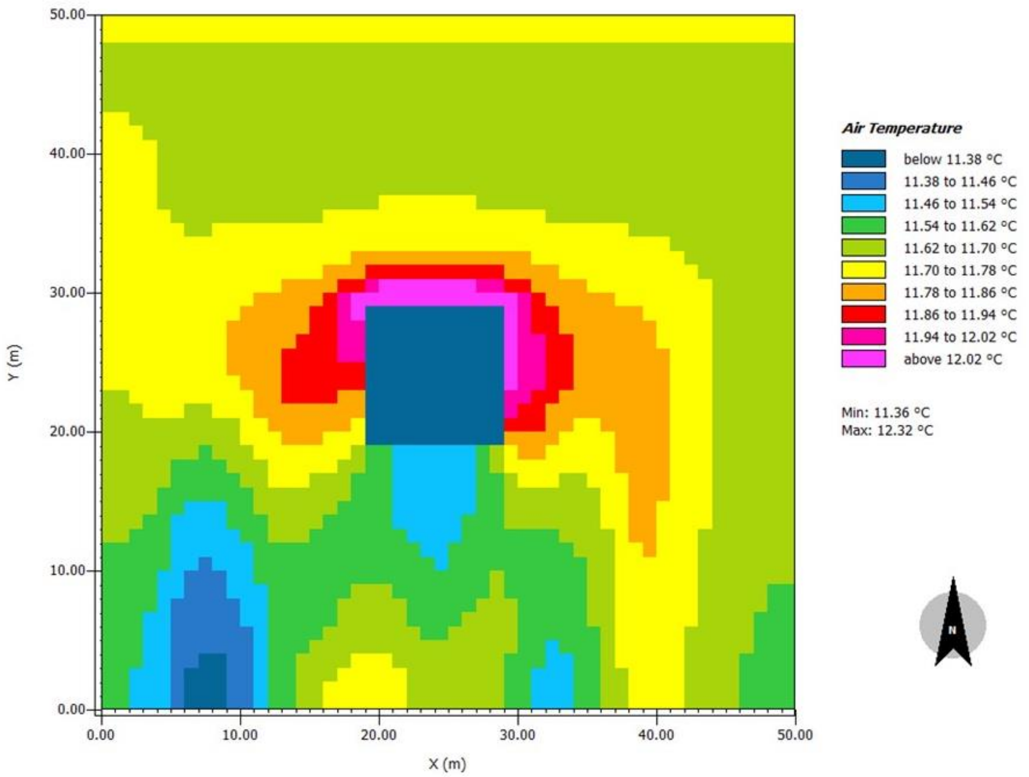


Figure 8.12. The 2D map of air temperature analysis for the 12-conifers model at 12.00 on 23rd June

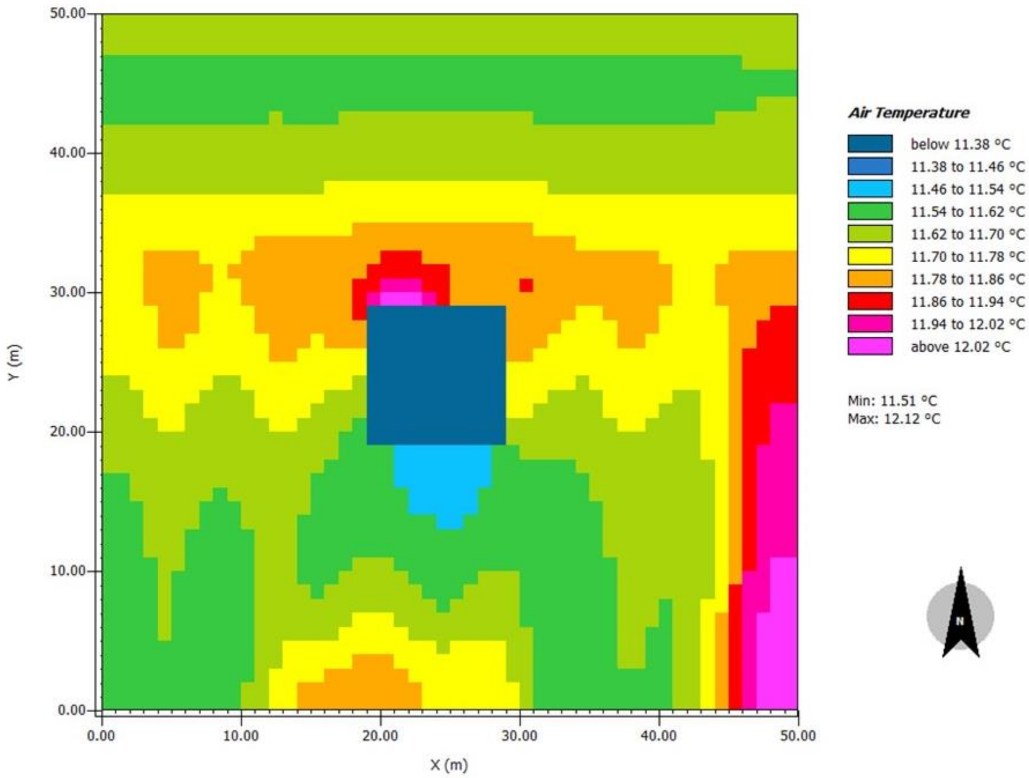


Figure 8.13. The 2D map of air temperature analysis for the 32-conifers model at 12.00 on 23rd June

The 12-conifers model produces warmer temperature surrounding the building, which is by 0.3°C higher than the open area (unobstructed area). Meanwhile, the 32-conifers model produces cooler temperature surrounding the building than the base and the 12-conifers models, but it has warmer area than the base model in the south and southeast of the building. The conifer-tree models produce an impact which is contrary to the literature review since they lead to a warmer temperature on the site.

In conclusion, the simulation results for the conifer-trees models (Diagram 8.29-8.32 and Figure 8.11-8.13) has the same trend as the previous tree-models' scenarios which applied the simple-plant model (section 8.7.3). In this case, the 3D-plant model, which is conifer-tree, also produce the contrary impact result to the literature review, likely due to cold winter weather applied in simulation - The tree shading in ENVI-met has no cooling effect on existing cold ambient temperature (see Section 8.7.6.2).

8.9. Conclusion: The impact of site in the ENVI-met model

From conducting the parametric test by integrating EnergyPlus and ENVI-met, it is concluded that the ENVI-met model produces the results which are not like the literature-review findings for almost all site impact on energy modelling (shown in section 8.6). Also, almost all site parameters have insignificant impact on house heating energy in energy modelling, which are less than 5%. The only one site parameter that produces significant impact like the literature-review findings is the ground surface material (6.9%).

The slope model generates unexpected results which are not like the literature-review findings because ENVI-met is limited to model the surface inclination of slope that can interact to microclimate system (Discussed in section 8.7.6.1) . The trees and nearby buildings scenarios in ENVI-met model almost have no impact in affecting microclimate for the case of Wellington. As discussed in 8.7.6.2, and 8.7.6.3, the insignificant impact of tree and nearby buildings are likely due to cold Wellington winter climate. Also, the height of nearby buildings in the parametric study is relatively low (3m and 6m), so this might lead the buildings producing an insignificant impact on local microclimate.

9. Conclusions

This section concludes with responses to three questions: the importance of site in energy modelling (Section 9.1), the usefulness of ENVI-met software in the Wellington (New Zealand) context (Section 9.2) and the idea of microclimate modelling in ENVI-met for use in energy modelling (Section 9.3).

9.1. How important is site in house heating energy modelling?

From conducting the parametric test of site-parameters modelling in EnergyPlus (Section 3.3), this thesis concludes that the four important site parameters – altitude, terrain, vegetation and nearby building– should be considered for house heating energy modelling in BES software. Those parameters generally simulate outcomes like those suggested in literature (See section 2.3 and 2.4) and can significantly influence the simulation results. The results of site modelling in EnergyPlus shows that the altitude difference of 100m can alter house heating energy by 16.5% through influencing outdoor air temperatures and wind factors in energy calculations. External objects representing slope, tree and nearby buildings can increase heating energy use by up to 8% due to their shading effect. Meanwhile, the terrain in EnergyPlus can contribute up to 32.2% due to the change of local wind speed -If the types terrain type is changed from suburb to ocean (see Table 3.7).

The parametric tests integrating EnergyPlus and ENVI-met (Section 0) revealed that only ground surface material can be an influential factor in affecting house heating energy modelling, which can increase the outdoor air temperature and affect energy consumption by 6.9%. Meanwhile, other parameters such as of slope inclination and orientation, as well as the nearby trees and buildings parameter have insignificant impact on house heating energy modelling (less than 5% besides the facing-south slope).

Table 9.1 summarises the importance of site parameters based on the parametric test in EnergyPlus and microclimate modelling using ENVI-met. Overall, the four important site parameters in EnergyPlus can produce the significant impacts on house heating energy simulation while ENVI-met could only produce significant impacts for one site parameter (ground-surface material). EnergyPlus can produce a significant impact of all four important site parameters by within 4.3% (shading effect) to 32.2% (terrain types affecting wind speed) although it is limited to model all aspects of important site parameters.

Site Parameters	Factor	Impact on house heating energy	
		EnergyPlus (Indoor)	With ENVI-met (Outdoor)
Altitude	100 m difference	16.5%	-
Terrain	Slope shade (facing-south)	8.3 %	-5.1% (Unmatched to literature)
	Seasonal effect (Facing-north slope)	Limited	1% (Insignificant & unmatched to literature)
	Terrain types (generalisation)	32.2% (from suburb to ocean terrain)	-
	Ground surface	Limited	Up to -6.9% -Pavement (Matched to literature)
Vegetation	Tree shade	4.3% (trees of 6m height)	-0.6% -12 trees in all direction (Insignificant & unmatched to literature)
	Number of trees (evapotranspiration)	Limited	-1.1% -60 trees in all direction (Insignificant & unmatched to literature)
	Leave density	2.2% (porosity of 75%)	-1.5% -Double LAD of 60 trees (Insignificant & unmatched to literature)
Nearby buildings	Building shade	8% (buildings of 10m tall)	-1.2% -building tall of 6m (Insignificant)
	Building surface	Limited	-2.4% -Concrete wall (Insignificant)

Table 9.1. Impact of site parameters on house heating energy based on the parametric test in EnergyPlus and ENVI-met

It was decided to not investigate the impact of external objects: slopes, trees and nearby buildings on the wind factor through ENVI-met simulation since ENVI-met mostly does not produce significant impact of site parameters matching those found in the literature review. In other words, conducting a test in ENVI-met to generate the wind data for weather file modification in EnergyPlus is not worthwhile. The impact of external objects as windbreaks on house heating energy modelling is a line of research that could be investigated in future work.

9.2. How useful is ENVI-met for microclimate modelling?

The application of ENVI-met basic version for microclimate modelling in energy modelling is not applicable for house heating energy modelling in Wellington context, New Zealand. Site parameters, which are considered important in the case the suburban area of Wellington, produces impacts which are insignificant and not like those found in literature review (see Table 9.1, Section 9.1). The insignificant impacts of tree and nearby buildings are likely due to the cold weather condition (winter in Wellington) applied in simulation (discussed in section 8.7.6.2).

Also, it was found that ENVI-met is limited to model the slope parameter, which led to unexpected impact of slope scenarios in the parametric tests (see section 8.7.6.1).

Reflecting on previous studies using ENVI-met (Section 8.7.6.3), the use of ENVI-met can be useful for simulating site-parameters effect in warm or hot weather condition and especially in urban context where the microclimate is strongly influenced by the built environment. The built-environment elements such as impervious ground surface and building facades can significantly influence microclimate and building energy use. The simulation results from section 8.6 show that only the ground surface-material (dark pavement) has a significant impact on reducing house heating energy due to its heating effect. In an urban area, a building-site can be surrounded by the car park or street with pavement or asphalt surface. Also, when the nearby buildings in an urban area are relatively tall and dense, the ambient temperature can change significantly because the effect of building's shading and facade material.

9.3. Microclimate modelling in ENVI-met for energy modelling: Is it worthwhile?

From the process of ENVI-met model evaluation (Section 7.4) and integrating ENVI-met with EnergyPlus (Section 0), it is concluded that the idea of microclimate modelling using basic version of ENVI-met for energy-modelling in not worthwhile. There are limitations and issues of microclimate modelling using from ENVI-met for the energy-modelling purpose:

1. **Computational time and limited results of only one-day microclimate data.** Based on parametric test of ENVI-met basic input (Section 7.3) and model evaluation (Section 7.4), ENVI-met takes about 6 to 7 hours of computational time in order to produce reliable results for a domain area of 50mx50mx25m (with 1m of grid cell), and the results produced by ENVI-met are only available for one-day microclimate data (24 hours). EnergyPlus can calculate annual energy use in no more than 10 minutes for the simple model in the parametric test - The simulation was conducted in PC with intel core i7 processor and 16 GB RAM.
2. **The validity of object and material in ENVI-met database.** The asphalt material from ENVI-met database does not produce the heating effect as suggested through the literature review (see section 7.4.2). However, another impervious layer, dark pavement, does. This raised the question of how much the material and object in ENVI-met database match with reality so that the model can produce reliable results – for example, whether asphalt in the model accurately represents asphalt in New Zealand. Also, ENVI-met provides detailed property inputs for the ground material and tree object, which are difficult to assume when considering

the real conditions of a site – for example, how to assume the water content value of soil or Leaf Area Density (LAD) of a tree on the real site. Meanwhile, there is a lack of documentation about general assumption or physics explanation related to these detailed inputs.

3. **The limitation of solar radiation.** As demonstrated in the model evaluation (section 7.4), ENVI-met can only model microclimate data based on a sunny day (clear sky condition). This is because the ENVI-met basic version can only adjust solar radiation based on multiplier factor from 1.0 (clear sky) to 0.0 and cannot input solar radiation based on the weather data, which is influenced by the cloud cover (see section 7.4.3). The Diagram 7.64 in Section 7.4.4 shows the direct solar radiation in ENVI-met model is much higher than that in the weather data while the diffuse solar radiation in the model is much lower. This might lead to inaccuracy of microclimate data produced by ENVI-met model for some cases.
4. **Deciding the ideal setting for the basic input.** There is a lack of documentation or guidance of how to decide or assume the ideal basic input parameters in ENVI-met in relation to reality – for example, how large should the domain area be for some cases or to what degree should the wind speed value be based on the weather data. This can be an issue for the users to trust the input setting for producing reliable results in an efficient way. In this thesis, an effort has been made to examine how the ENVI-met model behaves to basic input parameters through a parametric test of basic inputs in section 7.3 and model evaluation 7.4. The establishment of the ideal settings and a basic input configuration for the basic version of ENVI-met has been created as shown in section 7.5. This can be useful information for people using ENVI-met to create reliable model in an efficient way.

However, it is possible that these limitations will be solved in the future as ENVI-met software is still under development and new update releases every year with new features. For example, ENVI-met V4.4 (2018-2019) provides full-forcing feature that enable to model diurnal windspeed and direction as well as solar radiation based on the weather data (ENVI_MET, 2019). This feature can lead ENVI-met to produce more accurate and realistic microclimate data. Nevertheless, this feature is not in the basic (free) version – only in the full-paid version. With an advance of digital technology, it is likely that computational time of ENVI-met can be reduced in the future by new CPU system, which can lead ENVI-met to efficiently produce seasonal or even annual microclimate data for energy modelling.

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