Anthropogenic Heat Sources in Singapore

DELIVERABLE TECHNICAL REPORT

Version 1 - 13/09/2019

D 1.2.2.1 – ANTHROPOGENIC HEAT SOURCES IN SINGAPORE

Project ID	NRF2019VSG-UCD-001
Project Title	**Cooling Singapore 1.5: Virtual Singapore Urban Climate Design**
Work Package ID	WP1.2. Environmental assessment report
Deliverable ID	D1.2.2.1 – Anthropogenic Heat Sources in Singapore
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Date of Report	13/09/2019
DOI	https://doi.org/10.3929/ethz-b-000363683

Version	Date	Modifications	Reviewed by:
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ABSTRACT

This report describes the sources of *anthropogenic heat* (AH) in Singapore for the year 2016. The objective of this report is two-fold: first, to deliver a Sankey diagram of the main sources of AH in Singapore; and second, to explain all the definitions, assumptions, methods and outstanding uncertainties. We also provide our definition of AH in the context of Cooling Singapore 1.5. This is important for both Cooling Singapore and its stakeholders, since our results serve as the cornerstone for 1) validating any mathematical or physical approximation of the AH contributions in Singapore, and 2) analyzing the impact of AH on the Urban Heat Island (UHI) effect and subsequently on Outdoor Thermal Comfort (OTC).

As most of our energy usage spontaneously decays into heat, this report is largely based on the 2018 Singapore Energy Statistics of the Energy Market Authority. However, to get a more comprehensive understanding, an analysis of the country oil balance, supply of natural gas, power stations including cogeneration, and the industrial sector is done. We focus on the *domestic* use of energy as we are accounting the heat released within Singapore's land territory[1].

We identified four major sources of AH in Singapore. These are *Power Plants* (including the grid; together release **3118 ktoe** of heat, or 15.3%); and the three end use sectors *Industry* (**11906 ktoe** or 58.5%), *Buildings* (**2430 ktoe** or 11.9%), and *Transport* (**2328 ktoe** or 11.4%). We also estimated the heat released by human metabolism, which contributes a minimal amount (**579 ktoe** or 2.8%). We also viewed the heat from power plants alternatively as indirect heat, and allocated this based on the demand of the end use sectors.

The Sankey diagram of the energy system including the AH sources in Singapore in 2016 is shown in Annex A. The underlying calculations are shown in Annex B. Finally, two simple analyses of the Sankey diagram can be found in Annex C.

[1] The geographical scope of our model excludes distant territories, any shipping activity in the maritime territory of Singapore, and Singapore's airspace.

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List of Definitions and Acronyms

*Terms with adapted or own definitions.

Heat-Related

Anthropogenic Heat*	Anthropogenic heat refers to the heat released to the environment as a result the following human activities: ● High-grade heat generated and low-grade heat lost by power plants ● Heat generated by industrial activities ● Heat generated within commercial, residential and service-related buildings ● Heat generated by road and rail transport ● Human metabolism We specifically exclude these sources: ● Heat generated by other forms of transport, such as maritime and air traffic. ● Miscellaneous sources, such as public lighting, fires from accidents, wildfires, etc.
Direct Heat	Anthropogenic heat released directly by the specified activity, where the activity occurred.
Indirect Heat	Anthropogenic heat released by an upstream process to serve the specified activity. Indirect heat is not released where the activity occurred, but in another location. As an example, the heat from electricity generation is a direct emission of power plants, but an indirect emission of electricity consumption.
Sensible Heat	Sensible heat is the type of heat exchange accompanied with change in temperature. In our context, this encompasses the heat sources which increase air temperature, and therefore contribute to the Urban Heat Island. Furthermore, we also consider the influence of power plants that dump heat to nearby bodies of water.
Latent Heat	Latent heat is the energy exchange required for matter to undergo a phase change, during which the temperature of the substance stays constant. In our context, we usually refer to the vaporization of water, which leads to a localized increase in humidity.
Grade of heat (high or low)	This is a loose description of the usefulness of heat (i.e. the availability of work to be extracted from this heat) as implied by the Second Law of Thermodynamics. A good indicator for the heat grade is its source temperature, wherein higher temperatures (e.g. from combusted fuel) correspond to higher

	grades. Conversely, low-temperature heat is almost useless, unless significant amounts of heat are available.
Exothermic and endothermic	Exothermic reactions are chemical reactions that release energy, usually in the form of heat (e.g. combustion). The converse is true for endothermic reactions. This heat is usually expressed in terms of the change of enthalpy of the products and reactants. Complex processes usually involve multiple reaction steps, and the overall heat of the reaction is simply obtained via summing enthalpy changes.
Enthalpy	Enthalpy is a thermodynamic property which is defined as the sum of a substance's internal energy and the product of its pressure and volume. Enthalpy changes represent both the energy released/ absorbed as heat and any pressure-volume work that the process might incur.

General

Primary Energy	Energy that is found in its original natural form, which could have been extracted but still unprocessed. Examples include crude oil, wind, solar radiation, nuclear energy in uranium, coal, etc. The definition is typically extended to include secondary oil (i.e. petroleum products) when talking about all the energy products entering a well-defined energy system, such as that of a country.
Total Final Consumption (TFC)	Final consumption refers to the final demand of energy by the end user, which is often expressed per energy carrier (e.g. electricity, natural gas, process heat, petroleum products, etc.). Total final consumption is an aggregation of final consumption, either per end use category, per energy carrier, both, or over all energy carriers and end use categories. This is often expressed over one year.
End use	End use refers to the final consumption of energy products by customers, who then pay for it. This energy is not converted to other energy products nor sold later on. This encompasses both private and business usage. In modelling anthropogenic heat, we consider three *mutually exclusive* end use sectors: *Industry*, *Buildings* and *Transport*.

End use (cont'd)	As the EMA is our primary data source, we base our definitions of these sectors on their glossary (Energy Market Authority, 2017). These definitions are primarily based on energy requirements, and the economic sense is secondary. The EMA defines an "Others" category, which amounted to about 0.16% of the TFC in 2016 (Energy Market Authority, 2018), which we ignore. Thus, the three end use sectors are taken to be collectively exhaustive as well.
Industry*	*Industry* is an end use category which refers to all uses of energy for business activities related to the bulk production of physical goods and energy products, and to the provision of physical infrastructure (e.g. energy and water utilities). The precise definition is as given by the EMA's Glossary ("Industrial-related") (Energy Market Authority, 2017), in accordance with the Singapore Standard Industrial Classification 2015 (SSIC 2015), and is different with the definition used when measuring GDP as per the Department of Statistics. The logistics and distribution of intermediate or final goods via transportation is excluded here and covered under *Transport.*
Buildings*	*Buildings* refer to an end use category which is adapted from the EMA sectors "Commerce & Services-related" and "Households" (Energy Market Authority, 2017) taken together. Examples include: ● Residential – HDB flats, landed houses ● Commercial – offices, malls, retail ● Services – schools, hospitals, information and communications Office spaces that control industrial activities are not considered part of *Buildings*, but are under *Industry* instead. Structures such as empty containers are not contributors to anthropogenic heat and are excluded.
Transport*	*Transport* is the end use category referring to energy used for movement of humans and goods utilizing land transit vehicles including automobiles, buses, minibuses, vans, lorries, motorcycles, and trains. It is based on the "Transport-related" category of the EMA (Energy Market Authority, 2017). It excludes energy used for movement of aircrafts, ships, and military and human-powered vehicles.
LNG	Liquefied natural gas
PNG	Piped natural gas
GDP	Gross domestic product

WRF	Weather Research and Forecasting model. Used in Cooling Singapore to conduct mesoscale analysis of the Urban Heat Island effect in the country.

Petroleum-related

Domestic, inland oil demand*	Total demand of crude and petroleum products used within Singapore, excluding the oil for bunkering.
Oil	Unless otherwise specified, this refers to *both* crude oil (including shale oil) and refined petroleum products.
Energetic use of oil	The use of oil (usu. refined petroleum) as fuels or as precursors of fuel. These are combusted at final-use, and the released high-grade heat is used to run chemical processes, space heating and engines (from the scale of vehicles up to power generation).
Non-energetic use of oil	The use of oil (usually refined petroleum) for non-fuel purposes, such as wax, lubricants, asphalt and chemical feedstock (International Energy Agency, 2019). These products are *not* combusted but may release heat at the end-of-life *if* they are incinerated as waste.
Oil demand without anthropogenic heat*	Domestic, inland oil demand that does not *directly* contribute to the definition of anthropogenic heat for Cooling Singapore 1.5, as defined in this list. It is a superset of the non-energetic use of oil, and it may release heat *if* it is incinerated as waste. Its heat contribution may be included in the AH contribution of waste-to-energy plants.
Bunkering	Oil bunkering is the storage of fuels for use in international maritime transportation and international aviation.
NGL	Natural Gas Liquids

Electricity-related

Autoproducers	Term used to distinguish on-site, private generation from main power plants. The former typically produces electricity for its own use, whereas the latter provides electricity for Singapore in general (Energy Market Authority, 2017).
CCGT	Combined cycle gas turbine

Combined Heat and Power / Cogeneration	A combined heat and power plant, also known as cogeneration, is a power plant that produces both electricity and process heat.
Cogeneration CCGT	A cogeneration CCGT plant operates the combined cycle gas turbine with additional heat recovery stages, to produce heated water and/or steam.
Gross Electricity Produced	The total electricity output of all generators in Singapore, as measured from the generator terminals. The electricity used by these stations (i.e. in-house loads) and further downstream losses have not been subtracted from this.
Heat-to-Power ratio	The ratio of heat and power output of a cogeneration plant.

Buildings-related

Local Climate Zones (LCZ)	A classification scheme comprised of multiple zones based mainly on properties of surface structure and surface cover. Each zone is local in scale, meaning it represents horizontal distances of 100s of meters to several kilometers. (Stewart, 2012)
Evaporative Cooling	Evaporative cooling is a process that uses the effect of evaporation as a natural heat sink. Sensible heat from the air is absorbed to be used as latent heat necessary to evaporate water. This is the process of how most cooling towers work.
Dehumidification	Process of removal of moisture from air.

List of Uncertainties

Although the EMA energy statistics (Energy Market Authority, 2018) contains valuable information to underpin the analysis of anthropogenic heat in Singapore, it does not contain all that is necessary. Most of the uncertainties are from the lack of specification. Moreover, some of EMA's definitions are not strictly the same as the definitions used by the IEA. Finally, there are certain topics that are outside the scope of energy statistics, and do not have authoritative public reports for Singapore (e.g. miscellaneous heat sources).

IEA data (International Energy Agency) was used as a secondary energy statistics resource. However, we have observed a few marked inconsistencies with the two datasets, and take the EMA data to be more authoritative.

Listed below are the outstanding uncertainties.

Major Uncertainties

Description	Sec.	Additional information	Introduced error in relevant AH
Unknown use of unrefined crude oil	3.1	At least 5095 ktoe of unrefined crude was not used by refineries nor stored as stock. The actual amount is larger than this because the crude input to refineries is bundled with natural gas liquids. As Table 3.13 (Energy Market Authority, 2018) indicates that no sector purchases crude, the use of this crude remains unresolved.	*In the best case, the discrepancy is with the stock exchange or refinery inputs data.* *In the worst case, this crude is burnt and an additional 5095 ktoe of heat should be added to Industry.*
Industry oil demand is purely energetic	4.2	Whereas the IEA reports demand of oil and petroleum products as either energetic or non-energetic, the EMA did not specify this.	*Unknown, but optimistically none*
Unknown absorbed energy in industrial activities	4.2	*Industry* is complex and heterogeneous, and public data is scanty. We have calculated the released heat of *Industry* as the sum of all its energy demands, assuming that none of is absorbed.	*Unknown, but could be in the range of a few tens of percentage of the total energy demand.*
No data on cogeneration heat demand	4.1	Cogeneration plants serve nearby industrial customers with process heat. EMA does not report data on this market. We have estimated an upper bound of this heat.	*Unknown. Need to estimate total process heat*

No data on cogeneration heat demand (cont'd)			*requirements of Industry to verify.*

Buildings-related

Description	**Sec.**	**Additional information**	**Introduced error in relevant AH**
Energy considered as anthropogenic heat by the buildings	4.3	The energy consumed by buildings is not necessarily the equivalent anthropogenic heat released to the environment. For example, part of the energy used for water heating is dissipated by pipes and into sewage systems.	*Up to a few hundreds of ktoe*
The *Buildings* end use sector is not completely homogeneous in terms of energy consumption characteristics.	4.3	*Buildings* was defined in accordance to EMA's "Commerce & Services-related" and "Households" sectors, which includes industry-like subsectors such as information and communication. Such members have specific energy consumption profiles, and makes the sector less homogeneous. There is a potential overlap with *Industry*, which has to be carefully considered in downscaling.	*None, but complicates downscaling*

Transport-related

Description	**Sec.**	**Additional information**	**Introduced error in relevant AH**
Energy used by vehicles commuting from abroad	4.4	Vehicles that enter the city through customs might have purchased their fuel outside of Singapore, however, they are burning it in Singapore. Therefore, the energy they use might not be included in what is reported by EMA/IEA. However, vehicles that have purchased fuel in Singapore might also burn this fuel abroad, which counteracts the effect.	*<=5% of AH due to transport*
Energy consumed by military operations	4.4	The energy consumed by military operations in Singapore is not reported. Fuel for aviation training could be a significant amount, however, since this fuel is burned relatively high it might not be a significant factor for UHI.	*Unknown*
Energy for domestic maritime and aviation activities	4.4	It is unclear what falls in the category domestic maritime and aviation activities in the case of Singapore.	*Unknown*

Transport-related (cont'd)

Heat release at sea level in proximity to Singapore due to international maritime and aviation activities	4.4	Airplanes and ships that are on international routes use significant amount of energy at the Singapore port/airport which are either in the city or very close to it. This energy is not currently included in our AH estimations since it is not reported by EMA/IEA.	*~30-60% of AH due to transport*

Petroleum-related

Description	Sec.	Additional information	Introduced error in relevant AH
Unknown heat released in refining	3.1	To estimate the heat released by refineries, we would need information on the processes and how much of each petroleum product (and possibly natural gas as a by-product) is produced.	*A few hundred ktoe.*
Breakdown of crude and natural gas liquid in refinery input	3.1		*None*

Natural gas-related

Description	Sec.	Additional information	Introduced error in relevant AH
No town gas production and (incomplete) consumption data	3.2	The EMA bundles town gas consumption with that of natural gas. Singapore derives its town gas from natural gas, meaning a small portion of the natural gas consumption (in the order of 1% of the total natural gas consumption) is actually what is needed to serve the town gas demand.	*None, but complicates downscaling*

Miscellaneous

Description	Sec.	Additional information	Introduced error in relevant AH
Military operations, and other sensitive data for national security cannot be modelled.	-	The military uses transportation vehicles, operates bases, and so on. We will not attempt to model these sensitive sectors. However, it is expected that military bases have a small contribution in comparison to all other buildings.	*Unknown*
Any large-scale waste incineration that is not for waste-to-heat plants is not accounted	-	Such operations would not be seen in energy statistics, but are a source of heat. The Semakau Landfill is also considerably far from the main island.	*Unknown*
Human metabolism was roughly estimated.	4.5	Average metabolic rates were used, without accurate data for Singapore. The approach does not consider variations due to age, weight, sex, etc.	*Negligible*

1 Introduction

Anthropogenic heat sources in Singapore

Anthropogenic heat (AH) refers to the heat released to the environment as a result of human activities. These include:

- High-grade heat generated and low-grade heat lost by power plants[2]
- Heat generated by industrial activities[3]
- Heat generated within commercial, residential and service-related buildings[4]
- Heat generated by road and rail transport
- Human metabolism

And exclude:

- Heat generated by other forms of transport, such as maritime and air.
- Heat from waste incineration at the Semakau Landfill.
- Miscellaneous sources, such as public lighting, material decay, fires from accidents, wildfires, etc. These sources are expected to contribute too little heat to justify for the modelling effort.

We define the geographical scope of our AH calculation as the Singapore mainland, which excludes distant territories, any shipping activity in the maritime territory of Singapore, and Singapore's airspace.

Anthropogenic heat is an important component to understand the Urban Heat Island (UHI), but it is not solely responsible for the phenomenon. The other factors are not the subject of this report. For example, buildings not only release heat from their energy consumption, but also the material from buildings, pavements and roads contribute in terms of how solar radiation gets absorbed and released. Moreover, the morphology from buildings can be key to determine the entrapment of heat into the urban environment. Climate variables, such as wind speed and humidity, are also key components in terms of evaluating urban warming.

Most if not all the energy we use spontaneously decay into heat[5]. This is why national energy statistics underpins our analysis. However, there are certain industrial processes that absorb energy in endothermic reactions. An example would be the production of hydrogen

[2] This includes both main producers and autoproducers (as per EMA definition).

[3] This includes other energy transformation processes such as petroleum refining, LNG regasification, town gas production, etc., and the own-use of energy utilities, such as the electrical and gas grids.

[4] The rejected heat by space cooling includes the absorbed energy from solar, which must be excluded to respect the energy balance in WRF.

[5] The timescale involved can be nearly instantaneous, as in the case of fuels for heating and many uses of electricity, or up to 10's of minutes, as in the braking of vehicles.

gas via electrolysis, which can then be used in fuel cells[6]. This topic is discussed further in Section 4.2, *Absorbed energy in industrial activity*.

Objectives

The aim of this report is to describe the sources of Anthropogenic Heat (AH) in Singapore for the year 2016.

The specific objectives of this report are:

1. To derive a Sankey diagram depicting the energy system and the main sources of AH in Singapore for the year 2016.
2. To explain all the definitions, assumptions, methods and outstanding uncertainties behind the calculations.

Significance

Our results will be used to:

1. Validate mathematical or physical approximations of the AH in Singapore, and
2. Analyze the impact per sector of the energy system on the Urban Heat Island (UHI) effect and subsequently on Outdoor Thermal Comfort (OTC).

[6] Typical commercial electrolysers have efficiencies in the range of 56-73% (Holladay, Hu, King, & Wang, 2009).

2 Data Sources

We analyzed two public data sources: the 2018 Singapore Energy Statistics (SES), our main and default source, published by the Energy Market Authority (EMA) (Energy Market Authority, 2018)[7]; and the Sankey diagrams published by the International Energy Agency (International Energy Agency, n.d.).

The SES provides country-level energy statistics, meant to quantify the various facets of Singapore's energy use. These macro-level statistics allows further understanding of the consumption patterns and supply strategy of the country, and also allows for cross-country comparison. The 2018 SES contains data up to 2016, and partial data up to 2018. We followed the SES sectoral organization as much as possible, and deviated only when necessary in terms of accounting heat[8]. Although the information contained in the 2018 SES was a very good starting point, there were certain areas that lacked the information we needed and/or provided in an aggregated level wherein we needed more specification[9]. Additional authoritative sources would be useful, such as industrial energy requirements discussed in (National Environment Agency; Economic Development Board, 2016).

The yearly IEA Sankey diagrams assist in portraying the whole energy flows of energy imports, exports, transformation and up to consumption for a given country. In general, the figures for compiling the energy balances are provided by the various national administrations (statistical agencies, ministries etc.), which either provide them directly or make them publicly available via websites and book publications[10].

It is worth noting that Singapore joined the IEA as an Association country in October 2016, which lead to improvements in data collection. According to the IEA:

"The IEA Secretariat, the Energy Market Authority and the National Climate Change Secretariat (NCCS) are working closely together on improving data quality for Singapore. Therefore, breaks in time series between 2008 and 2009 and differences in trends when compared to previous publications may occur for some statistics. Due to Singapore's large oil trade volume in comparison to its final oil consumption, slight disagreements of trade figures can have a significant impact on the energy balance of Singapore." (International Energy Agency, 2019)

The main sources for IEA (1992-2016) include:

- Direct communication with the Energy Market Authority, Singapore.
- Direct communication with the National Climate Change Secretariat (NCCS), Singapore, from 2013.

[7] Available in both a report (.pdf) and tables (.xlsx) form.
[8] As an example, the EMA has an aggregated petroleum demand for transportation, whereas we only needed the *road* transportation demand.
[9] A few examples: a) we had to conduct an oil balance analysis; b) petroleum products are bundled.
[10] Because the EMA is an authoritative source for Singapore, we used it as our main source and expected that majority of the IEA data came from EMA.

- Direct communication with the Solar Energy Research Institute of Singapore, 2011.
- Singapore Energy Statistics, Energy Market Authority, Singapore, various editions up to 2017.
- Yearbook of Statistics Singapore, Department of Statistics, Singapore, various editions up to 2017.
- The UN Energy Statistics Database.
- IEA Secretariat estimates.

The advantage of depicting energy statistics as a Sankey diagram is a clear understanding of the linkages of the different energy carriers, as well as the balance of inputs and outputs of intermediate processes. Since the IEA report relies in great part on data from Singapore agencies, we also conduct a comparison between the values reported by IEA and EMA to verify differences in considerations due to definitions or data sources. Any discrepancy in the numbers would propagate uncertainty in the AH estimations and therefore should be noted.

Differences between EMA and IEA datasets

Where these two datasets disagree, they can disagree considerably. Thus, part of our work was to observe these differences and determine a reasonable resolution as to which source to follow. In this section we briefly describe some of the points of inconsistency, discussing them in more detail in their respective sections as necessary.

1) Power Stations

Data for the past two 2 years (2015 and 2016) were inconsistent, with EMA reporting energy inputs around 10% higher than IEA, which was reflected in a higher natural gas import. For past years analyzed (2010-2014) the data was consistent. Our hypothesis is that the fuel input to autoproducers was underestimated by IEA in recent numbers, therefore we based our results on EMA reports. For electricity generated, the number was consistent.

2) Industry

The IEA reported an energetic and non-energetic oil demand (pls. see *Definitions*), whereas the EMA reported a single number. In comparison to IEA data, the numbers provided by EMA were in the scale of 40-65% lower than the *total* (energetic + non-energetic) oil consumption, but 40-55% higher than reported numbers of *energetic* oil demand. Therefore, it was unclear how to allocate the oil demand by industry reported by the EMA. We analyzed the country oil balance for a better understanding of this figure, as explained in Section 3.1.

3) Buildings

For 2016 data, the data provided by EMA was quite consistent with the numbers provided by IEA. The IEA reported electricity consumption around 6% higher than EMA, probably due to differences of sub-sectors considered and rounding errors.

4) Transportation

The EMA reported a petroleum demand that was about 10% higher than the IEA data. After a careful review of their definitions, we noticed that the EMA definition included domestic aviation (i.e. flight training, flights for leisure, etc.), whereas the IEA declared it as for road transport only. Since the heat generated by domestic aviation is mostly released at high altitudes, we consider this heat release as irrelevant and without a contribution to AH. Therefore, we used the IEA data on the road transport category (**2090 ktoe**) for the portion of the *Transport* petroleum demand that contributes to AH.

3 Overview of Singapore's Energy Sources

In this chapter, we conduct a survey of the Singaporean energy supply, to support our analysis of the anthropogenic heat sources.

3.1 Crude Oil and Petroleum Products

Oil industry in numbers

Singapore is a major oil trading hub, with a total import of crude and petroleum products nearly ten times its domestic, inland consumption. Table 1 shows the volume of oil trade in Singapore and gives a sense of scale of the industry in relation to how much AH it could be responsible for.

Table 1 Singapore 2016 oil industry volume in Mtoe

	Mtoe
Total crude and petroleum products (PP) Import	166.1
Total crude and PP Export	99.3
PP bunkering	54.6
Domestic, inland oil demand[11]	17.7

Singapore does not have oil reserves and supplies its own inland demand from imported crude oil that it refines, as well as from imported petroleum products. However, this demand is dwarfed by the volume it exports and it bunkers for international maritime and aviation activities. The 2016 Singapore supply-side oil balance is shown in Figure 1.

A major uncertainty – *Industry* petroleum demand

The motivation to analyze the country oil balance was to distinguish between industry's energetic and non-energetic use of oil (pls. see *Definitions*), wherein the IEA and EMA reported disagreeing values as shown in Table 2.

To deal with the inconsistencies of the EMA and IEA data, we conducted a simple oil balance analysis to determine if the quoted 6.55 Mtoe demand of *Industry* was purely energetic or not. Table 3 shows a portion of the balance analysis (see Annex B for full details), comparing the inland petroleum products demand reported by EMA with the total volume available to serve this demand.

[11] Total demand of crude and petroleum products used within Singapore, excluding the oil for bunkering.

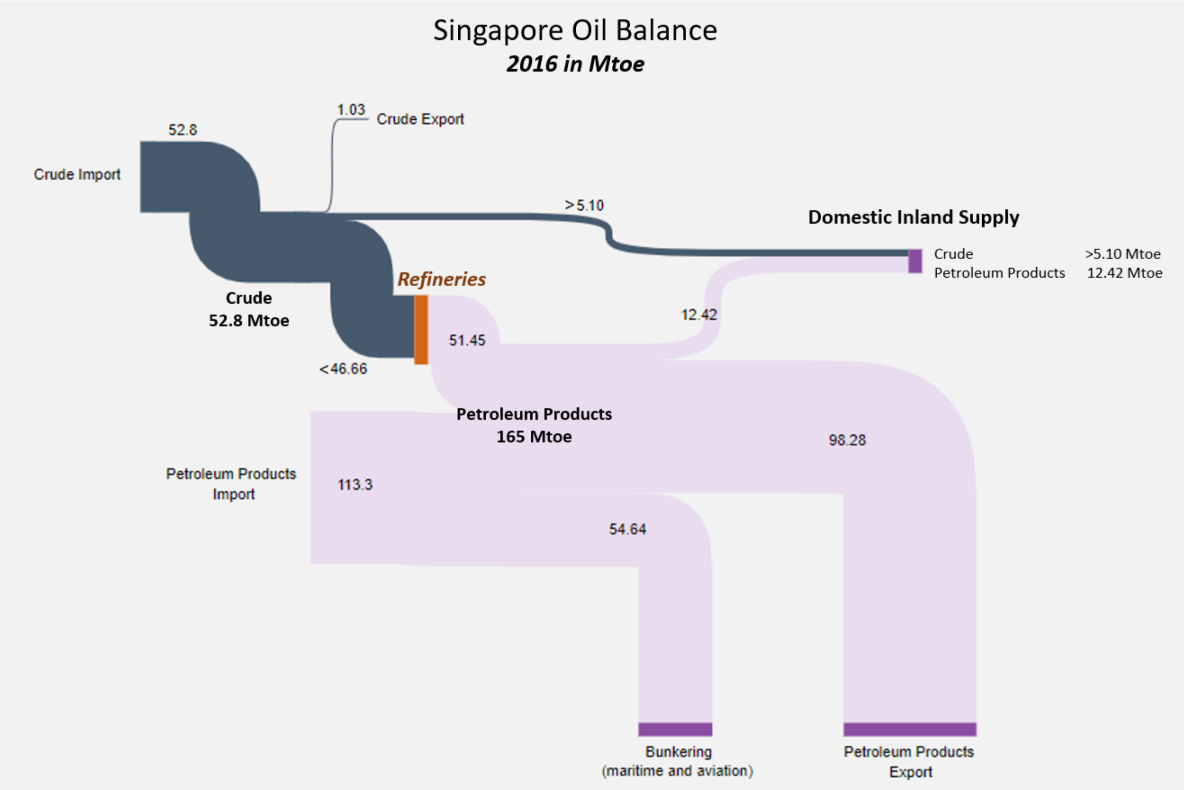

Figure 1 Singapore 2016 supply-side oil balance

Notes:

1) *Inland supply of petroleum products (12.42 Mtoe) is the starting flux of petroleum products in the AH Sankey diagram (Annex A).*
2) *EMA reports 46.65 Mtoe of crude oil and natural gas liquids as refinery inputs, which is why the input crude to refineries is less than this, and the same unknown amount is added to the domestic inland supply.*
3) *Stock exchanges for crude and petroleum products are too small to portray.*

Table 2 Industry oil demand inconsistency between the IEA and EMA

	Mtoe
IEA industry oil demand	**12.73**
Energetic, including industry own use	5.46
Non-energetic	7.27
EMA industry oil demand	**6.55**

After calculating the total oil volume (17654 ktoe) available to serve the demand calculated in the first half of Table 3 (9129 ktoe), we inferred that the demand listed by EMA on Table 3.12 (Energy Market Authority, 2018) was purely for energetic purposes. By doing this, we got a figure (8525 ktoe) for the non-energetic use of oil which roughly corresponded to the figure reported by the IEA (7270 ktoe). Acknowledging that this analysis is not definitive but is the best that can be done with the available data, we move forward with this assumption. A more careful energy audit of Singapore, especially with the energy needs of refining, can shed more light on this issue.

Table 3 Overview of Singapore 2016 oil balance, demand-side

Petroleum Products Demand	**ktoe**
Power generation	123
Industry	6554
Transport	2349
Commercial and services	77
Households	26
Total	**9129**

Oil Supply and Stock Draw	**ktoe**
Unrefined crude + NGLs	5095
Unrefined crude + NGLs Stock Draw	142
Net Petroleum Products import	15064
Refined Petroleum Products in SG	51453
Petroleum Products Stock Draw	541
Petroleum Products Bunkering *(based on IEA data)*	-54640
Total	**17654**
(inferred)	
Of which energetic	9129
Of which non-energetic	8525

Another major uncertainty – unspecified use of crude

After conducting the oil balance, a discrepancy in the data was discovered. As can be seen in Figure 1, there is a remaining amount of crude oil of at least **5095 ktoe** with an unspecified use (stock exchange has already been considered, as shown in Table 3). Crude is virtually only refined, rarely directly burnt and almost never used as feedstock outside refining. However, Table 3.13 (Energy Market Authority, 2018) clearly states that there is no end use demand of crude. Owing to the size, this is unlikely a statistical error. In the worst case, all of this crude is burnt by *Industry*, and its AH contribution potentially rises by the said amount. Alternatively, this crude could somehow be stored, or used for unspecified purposes.

Energetic Oil demand with and without AH contribution

As per our definition, *all* energetic uses of oil release heat, but not all of this is released within the geographic confines of our definition of anthropogenic heat, as explained in the Introduction. Specifically, the quoted 2349 ktoe of oil for transport also includes water and air, as per EMA definition (Energy Market Authority, 2017). On the other hand, the IEA reports an oil demand of 2090 ktoe just for road transport. We consider only road transportation and use the IEA figure, which is why 259 ktoe of the transportation oil demand diverges and contributes no heat in the Sankey. Table 4 details the breakdown of oil demand according to energetic vs. non-energetic, and with vs. without anthropogenic heat contribution.

Table 4 Oil demand breakdown

Via energetic use	**ktoe**
Energetic	9,129
Non-energetic	8,525
Via AH contribution	
With AH contribution	8,870
Without AH contribution	8,784

Both sum to 17654 ktoe

Refineries

Oil refineries are industrial facilities that process crude oil into petroleum products. Crude oil is a mixture of hydrocarbons of varying weight, which has to be separated primarily via distillation to create more useful products, collectively referred to as petroleum products. These products include not only a wide range of fuels such as gasoline, kerosene, LPG, diesel, etc., but also non-fuel products such as benzene, waxes, lubricants and bitumen.

EMA reports the input crude, natural gas liquids and other feedstock (total **53.30 Mtoe**) that entered the refining process, and the output products in terms of distillation properties[12] (total **51.45 Mtoe**; Table 2.6 (Energy Market Authority, 2018)). The difference in the energy content (**1852 ktoe**) could be attributed to:

- material losses (*aka* mass or oil losses)
- refining by-products[13]
- heat absorbed by petrochemicals production, whose processes are generally overall endothermic
- heat released by hydrogenation (for desulphurization), an exothermic process

[12] These are the light distillates, middle distillates and heavy distillates together with the residuum.
[13] These are the natural gas originally in crude, as well as off-gases produced in various processes. These gases are burnt to drive other refining processes.

Of these, only the last three contribute to the AH released by refineries. Detailed process information is required to calculate this, and we currently have very limited data. As mentioned in section 4.2 *Industry*, the refining sector is important to model, owing to the scale of its operation. In general, the AH released can be expressed as

$$refineries\ heat = input\ energy\ carriers - \Delta H_{\substack{by-product \\ combustion}} - \Delta H_{\substack{petrochemical \\ production}} - \Delta H_{desulphurization} \quad (1)$$

where,

input energy carriers	energy carriers demanded by refineries, which includes electricity and any of process heat, natural gas and petroleum products
ΔH	overall enthalpy change of the process

Separate from the energy content of the inputs and outputs is the energy requirement to refine these products, which is included in the first two terms of (1). This is about 5%-10% of their energy content (Blok, 2006), or around 2570 ktoe - 5145 ktoe for Singapore in 2016. Refineries in Singapore need about ten times as much heat[14] as they need electricity (National Environment Agency; Economic Development Board, 2016), which is more economically sourced from combusting fuels than from electricity[15]. This heat is likely sourced from cogeneration heat[16] and refining by-products; and possibly natural gas and cheaper petroleum products. This energy requirement is considered as end use, and is part of *Industry* demand.

Other uncertainties – data from IEA

We used two data points from the IEA to complete our analysis: 1) oil demand for road transport; and 2) amount of bunkering fuel. Our stance is that EMA data is more reliable than that of the IEA, so we emphasize that these two figures came from the latter. For 2016, oil demand for road transportation was reported as 2.09 Mtoe and bunkering fuel was 54.64 Mtoe.

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[14] This process heat is used in distillation, to maintain high temperatures in reactions, and to produce steam.

[15] Thermal generation at best achieves about 60-65% efficiency. Thus, if high-grade heat is needed, it is more efficient to burn fuels directly than to source it from thermally generated electricity.

[16] ExxonMobil owns on-site cogeneration plants (ExxonMobil, 2017). There are other cogeneration plants located in Jurong Island, and the strategic proximity suggests that other refineries could also source heat from these.

3.2 Natural Gas

Natural gas is an important commodity for Singapore, as about 95% of its electricity is produced from the fuel. Singapore imports all of its gas: **7419 ktoe** as 1) piped natural gas (PNG) from Malaysia and Indonesia, and **2262 ktoe** as 2) liquefied natural gas (LNG) from the global market.

LNG Regasification and Storage

The Singapore LNG Terminal (SLNG) functions as Singapore's LNG docking, storage and regasification facility. Providing 2262 ktoe of regasified natural gas in 2016, the regasification facility used a mere 1.82 Mt of its then 6 Mtpa capacity[17] (Energy Market Authority, 2017).

LNG can also be stored and reloaded to ships, whenever arbitrage opportunities exist in the market. However, EMA reported no LNG exports in 2016, suggesting limited arbitrage. The handling, storage and regasification of LNG is not without material losses[18], but the efficiency was determined to be nearly 100% with a simple balance calculation as shown in Table 5.

Table 5 Singapore 2016 natural gas balance

Supply	**ktoe**
Imported PNG	7419
Gasified LNG	2262
Stock Exchange	52
Total	**9732**
Demand	
Power Generation	8364
Industry	1193
Commercial, residential and others	167
Statistical difference	-4
Total	**9732**

[17] In September 2017, the regasification capacity was upgraded to about 11 Mtpa, but the LNG import amounted to only 2.20 Mt in 2017.

[18] For example, due to LNG boil-off.

LNG as a cooling source

LNG is produced by cooling natural gas down to -162°C at nearly atmospheric pressure. Upon regasification, the LNG simply requires heat to vaporize. Currently, the SLNG Terminal uses seawater as heat source and additionally has a combustion vaporizer for peak throughput (Singapore LNG Corporation, 2014). Gasifying the LNG via seawater is a form of anthropogenic cooling, and feasibility studies suggest that the most profitable use would be low-temperature industrial cooling (Subramanian, Berger, & Tunçer, 2017).

Uses of natural gas and error due to town gas

As already mentioned, Singapore chose natural gas as its primary fuel source for electricity generation. Apart from this, there are industrial energetic uses of natural gas, mostly for process heating. Finally, Singapore also produces town gas from natural gas, as provided by City Gas Pte. Ltd. Town gas is mostly used for cooking and heating by residential and commercial customers (Energy Market Authority, 2017), but there are industrial uses as well.

However, the EMA does not publish town gas production data, but only the **60.85 ktoe** consumption of the residential sector. The EMA bundles town gas consumption with natural gas, i.e. part of the natural gas consumed is actually what City Gas converted to serve the town gas demand (Energy Market Authority, 2017). No further investigation of this has been done, but this will introduce error to the downscaling of the AH from natural gas consumption, which is currently tied to end use. This error is not significant though, because town gas consumption is in the order of 1% of the total natural gas consumption.

3.3 Other Energy Sources

Other minor sources of energy (<5%) include Coal (~2%) and Waste/ Biomass/ Others (~3%). Coal is used in electricity generation, as well as in end use industry, while waste and biomass are primarily used in Waste-to-Energy plants for electricity production.

Solar production would fall under the “Others” category, but the current level of PV is small, just offsets the demand of PV owners, and is probably not measured by the EMA. Thus, virtually all of Singapore’s power generation is thermal.

4 Anthropogenic Heat Sources

4.1 Power Stations

Power stations are facilities that are primarily responsible for generating electricity[19], and also include cogeneration facilities. In 2016, Singapore had a generation fleet amounting to 13400 MW, with a peak demand of about 6800 MW. About 95% of its electricity is generated from natural gas via CCGT and Combined Heat and Power (cogeneration) CCGT units, a lot of which are clustered in Jurong Island and in Tuas. In 2016, the gross electricity production[20] was **4436 ktoe**, and **4181 ktoe** was delivered to consumers. Because the generation fleet is fully thermal, the heat produced by this sector is the difference between the total fuel input and the gross production, which is composed of the following:

1. waste heat lost in power stations
2. high-grade heat generated by cogeneration plants

Additionally, there is electricity lost in the transmission and distribution to customers, which is attributed to the power grid[21] and is shown as the small **255 ktoe** flux after the gross production.

Cogeneration plants also produce process heat as a commodity for nearby industrial facilities. This heat flux is shown in light orange from power generation to *Industry*. Because this heat is used outside of power generation, and can only be released to the environment after use, the AH is credited to *Industry*. Unfortunately, no data is reported on the cogeneration heat output, but we are able to estimate an *upper bound* of **2235 ktoe** based on the following information (sub-bullet points indicate that the parent was based on the children):

- Cogeneration CCGT capacities, by PNG- and LNG-fueled stations
- Indicative average load factor, weighted by the capacity of PNG- and LNG-fueled stations
    - LNG imports, assuming all was for power generation
    - Natural gas input to power plants
    - CCGT indicative electrical efficiency (Energy Market Authority, 2014)[22]
- Cogeneration CCGT operational parameters, favoring heat production

An upper bound was estimated by optimizing the cogeneration heat-to-power ratio for heat production, whilst confining to realistic heat and electricity efficiencies of cogeneration CCGT plants. The full calculation can be seen in Annex B.

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[19] The entire discussion on power plants includes autoproducers.
[20] This is measured at the generator terminals, before in-house loads and further downstream losses.
[21] This includes I^2R losses, transformer losses, switching losses, etc. and is distributed along the underground cable system of Singapore. This does not include the own-use of the transmission and distribution sector, which is bundled under *Industry*.
[22] Used by the EMA to calculate the parameters of vesting contracts.

Furthermore, the manner in which power plants release heat varies, depending on what cooling technology they employ. This heat could be released in the air or in nearby bodies of water, and may or may not have latent heat. This has to be accounted for in the WRF analysis.

The power sector is responsible for **3118 ktoe** (15.3%) of the *direct* anthropogenic heat emissions (cogeneration heat excluded), but we could view this as *indirect* emissions to serve the energy demands of downstream actors[23]. Thus, this indirect AH can be allocated according to their electricity consumption[24], which would help aid in understanding the effects of adjusting the electricity demand of certain subsectors (e.g. the electrification of transport, as discussed in Annex C). This allocation is summarized in Table 6.

Table 6 Allocation of indirect heat from electricity to end use

End Use	Electricity Consumption	Indirect Heat from Electricity	Direct Heat	Direct + Indirect Anthropogenic Heat
Industry	1756	1317	11906*	13233
Buildings	2174	1631	2430	4062
Transport	227	170	2328	579

**Includes the high estimate of heat from cogeneration.*

Finally, our approach to downscale the heat from power generation would be to replicate the behavior of the National Electricity Market of Singapore, given the following information:

1. Power plant database, including capacities, locations, generation technologies and fuels.
2. Statistics on the electricity market (Energy Market Authority, 2018) (Energy Market Company, 2018)
3. EMA's Vesting Scheme (Energy Market Authority, 2019)

This market model would yield the power plant dispatch given the system demand, and the associated heat could then be estimated.

[23] Indirect heat is not unique to power plants. Pls. refer to Section 4.5, *Other Indirect Heat*.
[24] This was done assuming every kWh of electricity produces the same amount of heat.

4.2 Industry

Definition

Industry is an end use category that encompasses the bulk production of goods (including energy products) and the provision of physical infrastructure. The sectors of the Singaporean economy that fall under this category is defined by EMA in their "Industrial-related" sector (Energy Market Authority, 2017). We provide the following generic[25] examples in Table 7.

Table 7 Industrial activity examples

Production of physical goods	Production and delivery of energy products	Provision of physical infrastructure
• engines, electronics, tools • steel, welding and machining • food products • water treatment	• refineries • LNG storage, docking and regasification • district cooling • power plants (in-house loads) • power grid • gas grid	• water distribution • construction

Finer points regarding this definition include:

a) *Industry* includes very specific energy usages and absorbs most of the heterogeneity in the economy

As described in the definition of *end use*, the three end use sectors are taken to collectively exhaust all the domestic energy demand in Singapore[26]. A property unique to *Industry* is that its members have specific energy uses (see Table 7), and thus is the most heterogeneous sector. On the other hand, *Buildings* is treated less heterogeneously in terms of characterizing their energy usage[27].

b) Energy input vs. demand of energy transformation processes

Because this definition is given in the context of the energy value chain, it is important to distinguish the energy inputs to energy transformation processes (e.g. refineries, power plants, SLNG terminal) from the energy demand to *run* these processes, including any

[25] There might actually be no company in Singapore that does some of these, but this gives an idea of what would be considered as industrial activity.
[26] This might not include data on matters of military and defense.
[27] Pls. see Section 4.3 for more information.

overhead (e.g. electricity for the office). The former would *not* be counted in the *Industry* demand, whereas the latter would.

e.g. oil refineries

The input crude and other material feedstock would *not* count under *Industry*, but the process heating requirements in distillation, thermal cracking, etc. would. Whereas the crude is transformed to petroleum products, the heat requirements are not.

The energy requirements to run the refineries are shown under *Industry* in the Sankey diagram, whereas the crude input is shown in Figure 1.

c) **Logistics and distribution**

Although moving goods via road and rail is crucial to the operation of businesses, this part of their energy demand is covered in *Transport*.

Industry overview by primary energy consumption

The chemicals (petrochemicals and specialty chemicals) and petroleum refining are the dominant energy consumers in Singapore. Thus, they are the most valuable sectors to model, with the refining sector potentially being less heterogeneous. The share of primary energy consumption of major businesses[28] in 2010 is shown in Figure 2.

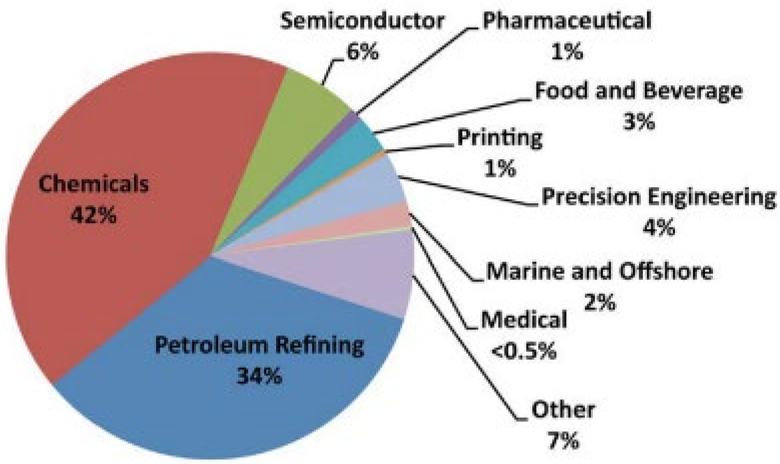

Figure 2 Primary energy consumption of major business in Singapore, 2010 (National Environment Agency; Economic Development Board, 2016)

[28] Pls. note that the listed sectors here do not fully align with the definition of *Industry*.

The energy requirements of chemicals and refining, as well as that of semiconductors and pharmaceuticals are also shown in (National Environment Agency; Economic Development Board, 2016). The average heat-to-power ratio of chemicals and refining is over 10, which explains why the majority of *Industry* demand is in the form of heat (i.e. cogeneration heat, coal, natural gas and petroleum).

Final consumption by carrier

EMA details a breakdown of the final consumption of various end use categories by energy as shown in Table 8. As discussed in Chapter 3, the petroleum products *Industry* demand is inferred to be all energetic, and the natural gas demand could be partially indirect demand and consumed as town gas.

Table 8 Total final consumption by carrier (Table 3.13, (Energy Market Authority, 2018))

2016 in ktoe	**Coal and Peat**	**Crude Oil**	**Petroleum Products**	**Natural Gas**	**Electricity**	**Total**
Total Final Energy Consumption	**166.8**	**-**	**9,006.4**	**1,360.2**	**4,181.1**	**14,714.6**
Industry-related	166.8	-	6,554.3	1,193.5	1,755.7	9,670.3
Commerce and Services-related	-	-	77.3	92.1	1,521.9	1,691.3
Transport-related	-	-	2,349.0	11.2	226.9	2,587.1
Households	-	-	25.8	60.9	652.6	739.2
Others	-	-	-	2.6	24.1	26.7

As discussed earlier, *Industry* is a broad, complicated and heterogeneous body. We could also see this in its diverse energy demand, while remembering that petroleum products refer to a wide array of energy carriers. However, this table lacks the *process heat* demand, or specifically the high-grade heat produced at cogeneration plants and sent to nearby customers. Unfortunately, this is as far as the available data reports, and we have no precise indication as to how much process heat is traded this way[29]. This missing information would not change the total AH calculation, but would be a problem for downscaling this heat.

Finally, *Industry* is clearly the largest consumer of energy. It thus is the most significant contributor to anthropogenic heat. However, it is interesting that the relative heat

[29]As discussed in Section 4.1 Power Stations, we have a high estimate of this. An industry heat demand analysis could further explain if enough heat is supplied to *Industry*.

contributions change if we factor in the indirect heat emission from electricity, noting that the *Buildings* demand is largely electricity.

Non-energetic demand of oil

In Section 3.1, we determined that about **3290 ktoe** of petroleum products were used for non-energetic purposes. Although likely purchased by actors that would fall under *Industry*, the material is not used for energetic purposes and therefore does not show up at end use. Consequently, we assume that they have *no* contributions to anthropogenic heat.

These are not burnt at end use, but a portion could be incinerated at end-of-life as part of waste treatment. If they are incinerated at waste-to-energy plants, then this heat would be accounted for under *Power Stations*. Otherwise, we simply ignore these and expect it to introduce negligible error.

Some examples of petroleum products that are not used for their energy content include:

- bitumen (ingredient of asphalt)
- waxes
- lubricants
- white spirit (solvent for paint)

Absorbed energy in industrial activity

The validity of having all the energy consumed by *Industry* eventually dissipate as anthropogenic heat is challenged by the following possibilities:

1. Some of the natural gas and petroleum products demanded by *Industry* were actually used to produce other types of fuels. Furthermore, these fuels could be exported, but not traced by the EMA. Thus, they do not release heat in Singapore.

   e.g. Hydrogen production by steam reforming of natural gas (if used for fuel cells).

2. Chemical processes for non-fuels that are overall endothermic. The products absorb a net amount of energy (i.e. their enthalpy increases).

   e.g.
   Hydrogen production by electrolysis of water (if used as a non-fuel).
   Catalytic reforming or condensation polymerization in the petrochemical industry, which produce high-value chemicals such as aromatics and polymers.

As per IEA definition (International Energy Agency, 2019)[30], the energetic use of fuels (e.g. natural gas and petroleum) also includes when these fuels are transformed to other fuels. If they are transformed, but used in Singapore (e.g. town gas from natural gas), then they still contribute to the anthropogenic heat[31]. If instead, they are exported and somehow not reported by EMA, then the energy content of the inputs is not released in Singapore. We have no further data on this, and this is a major uncertainty.

The second mechanism for absorbing energy in industrial processes might introduce less error. Although the chemicals and refining sectors are very large consumers of energy, endothermic reactions are not thermodynamically favored owing to the *decrease* in entropy of their surroundings. For endothermic reactions to proceed, the increase in entropy of the reacting system must overcome the entropy destruction, *and* a high enough temperature is needed to overcome the increase in enthalpy of the reacting system. This can be summarized by the requirements on the Gibbs free energy of the reacting system:

A reaction will proceed if

$$\Delta G_{sys} = \Delta H_{sys} - T\Delta S_{sys} < 0 \quad (2)$$

where,

Sys	The chemical reacting system, composed of both the products and would be reactants.
ΔG_{sys}	Change in the system Gibbs free energy, after the reaction.
ΔH_{sys}	Likewise; this is the system enthalpy.
ΔS_{sys}	Likewise; this is the system entropy.
T	The temperature of the reacting environment.

This then places thermodynamic limits as to how much of the input energy (which is needed to maintain a sufficient temperature conducive to the reaction) can be converted into high-grade chemical energy.

Conversely, there could be non-combustion exothermic processes[32]. Because these processes are not primarily for heating, we can assume that these contribute a negligible amount.

30 Pls. see "Non-energy use."
31 But downscaling to determine the location of the heat release is uncertain.
32 An example would be desulphurization, as mentioned in *Refineries* in Section 3.1.

We currently have insufficient information and data on *Industry* to make a reasonable estimate of the absorbed energy, so we neglect it for now[33]. Thus, we are potentially making a high estimate of the *Industry* anthropogenic heat.

Modelling approaches for Cooling Singapore 1.5

As mentioned earlier, downscaling the aggregated demand of *Industry* is especially challenging owing to the heterogeneity and specificity of industrial activity. On top of this, businesses tend to be unwilling to provide detailed data of their operations. However, owing to the evident weight this sector has, we would still labor to have its imprint in the model.

Our approach would be to identify key industries for which we could gather reasonable information and make reasonable models of their energy consumption. We would prioritize those that we know that are both heavy energy consumers and contribute significantly to the GDP, and those that are fairly easy to model. A few examples include: refineries and the Singapore LNG Terminal. The rest of the demand could at least be distributed uniformly in space and time along known industrial areas.

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33 To estimate the absorbed heat of endothermic reactions, we would need to know the chemical processes involved and the amount of the products.

4.3 Buildings

Buildings refer to an end use category which encompasses the following sub sectors:

- Residential: all households in their capacity as final consumers (Energy Market Authority, 2017). Encompasses HDB flats, condominiums and landed houses;
- Commercial: includes office and retail activities;
- Services: includes governmental buildings, schools, hospitals, information and communications, etc.

Commerce and Services consumption is defined by a list of sub-sectors, in accordance to SSIC 2015. (Energy Market Authority, 2017). Office spaces controlling industrial activities (e.g. command centres) or activities not listed in by SSIC would be classified under "Industry" and "Others", respectively.

In general, we consider buildings as built-up structures that consume energy for the particular uses listed above. Therefore, it excludes structures such as empty containers, which do not contribute to anthropogenic heat.

We assume the AH from buildings to be equal to the total energy consumed by them, as commonly done in the literature (Boehme, Berger, & Massier, 2015), (Ichinose, Shimodozono, & Hanaki, 1999), (Coutts, Beringer, & Tapper, 2007), (Sailor & Lu, 2004), (Quah & Roth, 2012). It is worth noting that this value is different from the heat ejected by air-conditioning, commonly referred to as the anthropogenic contribution from buildings (Stewart & Oke, 2012). The latter definition includes heat due to solar radiation (non-anthropogenic), as well as from metabolism. Additionally, there are other aspects that differentiate the energy consumed in buildings from the rejected sensible waste heat into the atmosphere (Heiple & Sailor, 2008):

- Part of the energy used for domestic water heating exits the building through pipes and into a sewage system.
- A small portion of energy consumption by appliances is converted to latent heat (e.g. coffee makers and ranges).
- Due to processes such as evaporative cooling and dehumidification, sensible waste heat exhausted from air conditioning systems is rarely the same as the energy consumed by their mechanical systems.

For now, we consider the total energy consumption of buildings as the anthropogenic heat, without distinguishing between sensible and latent components. This encompasses the main building heat sources, which are related to equipment and lighting usage, and eventually get transformed into heat. The metabolic heat of building occupants is considered separately (pls. see Section 4.5, *Human Metabolism*). This consideration is applicable to all buildings, even the ones that are naturally ventilated. Building energy consumption also includes all machinery outside the household units, such as the one required to operate lifts and cooling of common areas.

IEA indicates building energy consumption from residential sector and commerce/public service. EMA divides it between households and commerce/ service related. Furthermore, EMA provides information regarding the type of housing (landed properties, condominiums and public housing). Commerce and service related have their annual energy consumption divided into the following groups: Wholesale and Retail Trade; Accommodation and Food Services; Information and Communications; Financial and Insurance Activities; Real Estate Activities; Professional, Scientific and Technical, Administration and Support Activities; Other Commerce and Services-related.

In 2016, buildings consumed **2430 ktoe** of energy, with 2174 ktoe (~89%) from electricity. Oil products contributed 103 ktoe of energy consumed by buildings, while natural gas contributed 153 ktoe.

To downscale the total *Buildings* heat into spatiotemporal profiles, we use a bottom-up approach of district-scale building energy models (using the *City Energy Analyst* (Chair of Architecture and Building Systems, ETH Zurich, 2018)) for 50 areas in Singapore, equivalent to 14km² of land coverage and over 4000 buildings. The areas are selected according to different Local Climate Zones (LCZs), and the modelled districts are then extrapolated to the rest of the mainland via the LCZ classification. As such, the more homogeneous the *Buildings* sector is in term of its energy uses, the lower the expected error we can achieve with this approach[34]. Furthermore, this statistical model is used to handle model and sample uncertainties.

[34] *Buildings* was defined in accordance to EMA's "Commerce & Services-related" and "Households" sectors, which includes industry-like subsectors such as information and communication. Such members have specific energy consumption profiles, and makes the sector less homogeneous. This is a challenge we face, to abide by our primary data source.

4.4 Transport

Transport is the end use category referring to energy used for movement of humans and goods utilizing land transit vehicles including automobiles, buses, minibuses, vans, lorries, motorcycles, and trains. Vehicles which generate most of the heat away from the country (e.g. ships and planes) are not included, for not having a direct influence over anthropogenic heat impact in Singapore. Other vehicles that produce heat mainly via braking and friction (e.g. bicycles) are also excluded, due to its expected negligible impact on anthropogenic heat.

We assume the AH from transportation to be equal to the total energy consumption of this sector. In general, vehicles consume fossil fuels, which burn and generate energy for its movement. The energy that is lost in this conversion is almost immediately released as heat through the exhaust pipe, engine, tire friction, and braking discs of the vehicle. The energy that is used to move the car is eventually also transformed into heat; however, this process might take a significantly longer more time.

IEA subdivides the energy consumed by transport activity in Singapore into road, rail and domestic navigation. Road transport includes fuels used in road vehicles as well as agricultural and industrial highway use (excluding military consumption) and have been the biggest part of CS investigation, due to its significantly higher contribution.

EMA's definition of transported-related consumption combines the following subsectors: transport and storage, land transport, water transport (domestic navigation), air transport, warehousing and support activities for transportation and postal and courier activities. Although encompassing various subsectors, the total energy consumption is given in aggregated form for all transportation components.

In 2016, transportation consumed **2328 ktoe** of energy, excluding 259 ktoe which are assumed to be released out of Singapore's domains (in navigation and air transport, for example). Almost 90% (2090 ktoe) of the energy consumed is in the form of petroleum products, which are used by road vehicles. The remaining is consumed as electricity (227 ktoe) mostly by rail transport, and there is a trace amount of natural gas consumption (11 ktoe).

Future phases of Cooling Singapore aim to investigate the ground heat emissions at Changi airport caused by international aviation and also the emissions produced by all ships within the port of Singapore. If those emissions turn out to be significant and if they are produced close enough to impact the climate conditions on the island, they will be subsequently included in the Sankey diagram as well.

In order to assess the spatiotemporal distribution of AH emissions due to transport, we use a city-scale agent-based traffic simulation, CityMos (TUMCREATE, n.d.), which is capable of computing the amount of heat produced at every road segment in the Singapore road network on an hourly basis.

4.5 Other sources

Human Metabolism

Our bodies generate heat owing to our metabolism. This number can be approximated by assuming an average heat production rate by humans, and applying it to the whole population. Following a Singaporean study (Quah & Roth, 2012), we assume two different metabolic rates:

1. Daytime activity (171 W for 16 hours), during which humans are active.
2. Night-time activity (69 W for eight hours), during which humans are resting.

Based on these numbers, a single human produces on average 137 W per day. In 2016, Singapore had around 5.6 million people (SingStat, 2018). This is equivalent to around **579 ktoe** per year.

As metabolism is unrelated to modern use of energy, this is the sole component unrelated to energy statistics. It is often analysed in anthropogenic heat studies, therefore we also evaluate this component. Our estimate agrees with previous works (Ichinose, Shimodozono, & Hanaki, 1999), (Coutts, Beringer, & Tapper, 2007), (Sailor & Lu, 2004), (Quah & Roth, 2012) which reported a small contribution (<10%) in comparison to the total anthropogenic heat.

The spatiotemporal distribution of this component has not been explored in detail due its relatively small contribution. Furthermore, humans are mostly indoors, which is reflected in the energy consumption of buildings.

Other Indirect Heat

The concept of indirect heat was introduced in Section 4.1 Power Stations. However, indirect heat is not unique to the heat released by electricity generation. In general, we can define indirect heat as the heat released by upstream energy processes to provide downstream services[35]. Examples of these linkages in the energy system include:

- Heat released by the natural gas and town gas grids to serve gas
- Heat released by power grids to serve electricity
- Heat released by refineries to serve the domestic petroleum demand

Of the examples of indirect heat provided hitherto, the indirect heat from electricity generation is both significant and easiest to account for. The gas and power grids are expected to release much less heat, and we have no data to account for this precisely. Finally, the case for petroleum products is much more complicated, owing to the following factors:

[35] And this could be extended beyond heat, such as indirect CO_2 emissions.

1. EMA bundles petroleum products, and does not publish a breakdown.
2. Singapore has very strong import and export activity of petroleum products, and we do not have data on how much of the local demand is supplied from Singapore's refineries and from imports.
3. It is open to debate how to allocate the heat amongst the different petroleum products. Should it be based on energy content solely, or should market value count as well?

Owing to the large volume of crude refined in Singapore, a more in depth analysis of the heat released by refineries and of the allocation of this indirect heat is recommended for future work.

5 Conclusions

We have developed a Sankey diagram representing the energy system of Singapore in 2016 and the sources of anthropogenic heat (pls. see Annex A). This report details our survey of the energy system and includes our definitions, assumptions, methods and uncertainties.

We have analysed four major sources of heat: 1) power plants (including the power grid); and the three end use sectors 2) *Industry*, 3) *Buildings*, and 4) *Transport*. We also touched on human metabolism, and introduced the concept of indirect heat emissions. The results are summarized in Table 9 and visualized in Figure 3.

Table 9 Summary of Anthropogenic Heat (AH) in Singapore in 2016

Source	Direct AH [ktoe]		Indirect AH from electricity [ktoe]	Direct + Indirect AH [ktoe]	
Power plants and grid	3118	15.3%	-	-	
Industry	11906	58.5%	1317	13223	64.9%
Buildings	2430	11.9%	1631	4062	19.9%
Transport	2328	11.4%	179	2498	12.3%
Metabolism	579	2.8%	-	579	2.8%
Total	**20362**		**3118**	**20362**	

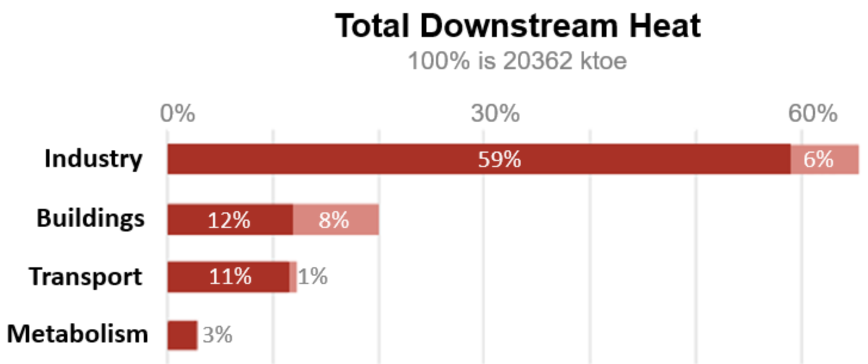

Figure 3 Direct and indirect downstream anthropogenic heat sources

The largest heat contributor is *Industry*, a heterogeneous sector with chemicals and refining as major subsectors. All major uncertainties are also related to *Industry*:

1. There is an outstanding amount of unrefined crude (5095 ktoe) in the domestic oil supply. This is a discrepancy in the EMA data, which in the worst case would lead to the same amount of heat released by *Industry* (pls. see Section 3.1).

2. Industry petroleum products demand (6554 ktoe) is inferred to be *all* energetic (pls. see Section 3.1).

3. Neglect any absorbed energy in industrial processes, such that the released heat is equal to the input energy (pls. see Section 4.2).

4. No data on cogeneration heat production by power plants. A high estimate (2235 ktoe) is used and serves as upper bound (pls. see Section 4.1).

Buildings is the next largest contributor, albeit with a large gap. As its energy requirements is mostly electricity, it has the largest relative increase when indirect heat is considered. Reducing the thermal emissions of electricity generation would reduce this indirect heat, but reducing electricity consumption would reduce *both* direct and indirect heat.

The Sankey diagram contains no information on the temperature of these heat sources, or whether they are released as sensible or latent heat. For the purposes of mesoscale analysis of the UHI effect in Singapore, these aggregate numbers have to be 1) downscaled and provided as spatiotemporal profiles; and 2) separated into sensible and latent heat.

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Annex A – Singapore 2016 Anthropogenic Heat Sources Sankey Diagram

Basic Pointers

1. **Type of Sankey**
   This Sankey diagram portrays the energy system of Singapore in 2016, including the associated heat emissions, as well as non-energy sources. Collectively, these are the anthropogenic heat sources.

2. **Purpose of the Sankey**
   Sankey diagrams of energy systems offer a macro-level view. They communicate the following:

   - *What* are the energy demands of the system (i.e. end use).
   - *How* does the source the input energy to serve the demand (i.e. domestic supply)
   - What *transformations* do the energy carriers undergo until they are fit for final consumption

   This Sankey has been augmented to also portray anthropogenic heat.

3. **Fluxes**
   Each flux represents a particular energy carrier, or class of carriers (as in the case of petroleum products). As a flow diagram, the width of the fluxes is proportional to the amount.

4. **Transformation Nodes**
   Intermediate nodes of the Sankey are best thought of as energy processes, as opposed to the physical facilities / infrastructure.

   e.g. Electricity Generation

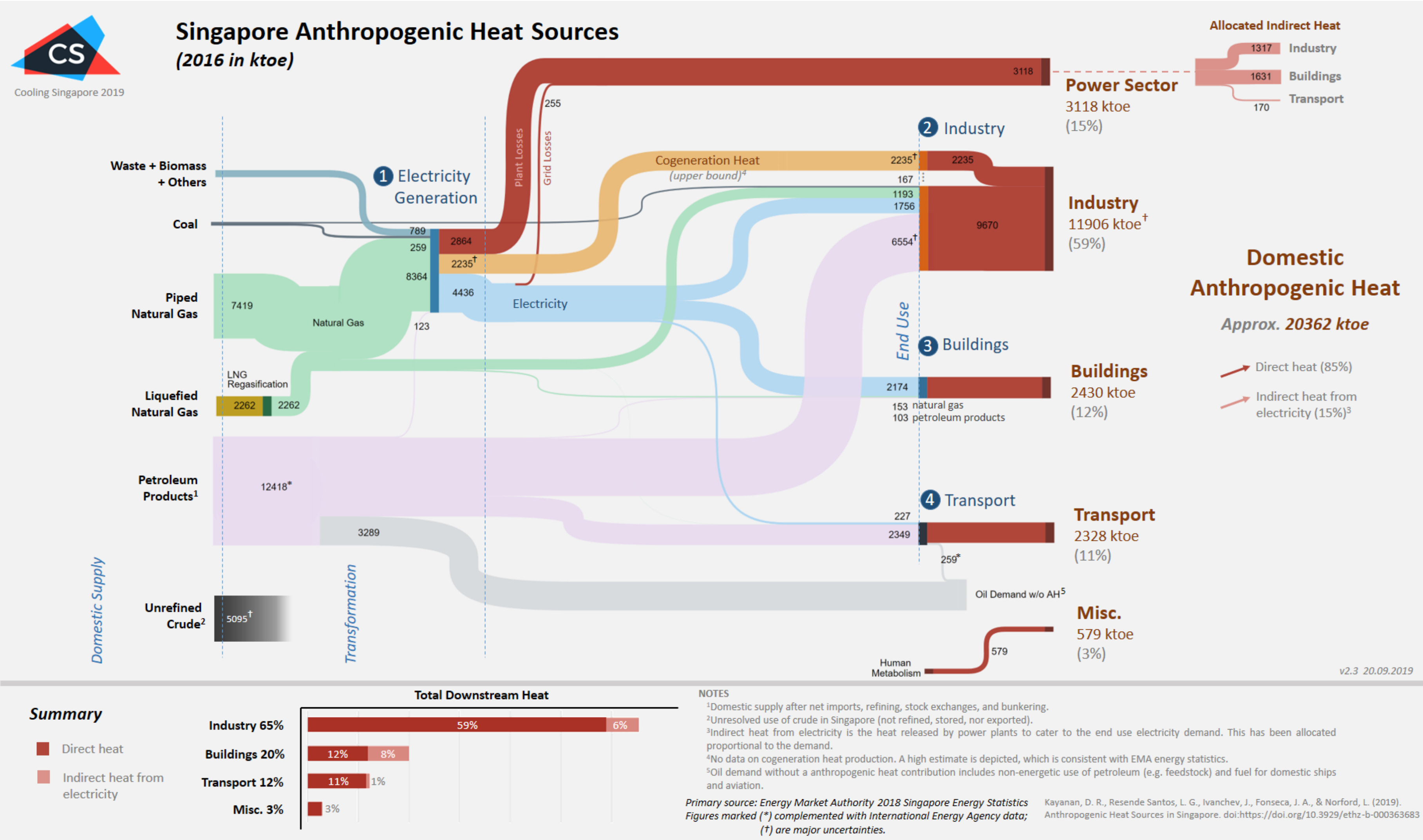
   Power plants consume electricity themselves, which is known as house loads. However, this consumption is not portrayed in the *Electricity Generation* node; rather, it is an end use consumption under the *Industry* sector.

Additional

Question Where is the crude refining node?

Answer Due to the very large scale of the petroleum industry compared to the domestic market, we could not represent the fluxes in the same scale. The refining process is shown in Figure 1 (p7), wherein the ending fluxes of petroleum products and crude (labelled *Domestic, Inland Supply*) correspond to the starting fluxes of these products in the Sankey diagram.

Made using the Sankey tool available at http://www.eco-data.fr/tools/sankey/start_en.php



Annex B – Spreadsheet of the Singapore 2016 Anthropogenic Heat Sources

Sankey AH sources v1.8.xlsx.

Supply-side

1a Waste/ Biomass

	IEA [ktoe]	EMA [ktoe]	%dif	Table in EMA 2018 Energy Statistics / Method
Into Main Power Producers		724.6		T2.1 Energy Flows for Electricity Generators
Into Autoproducers		64		T2.1
Bio/ Waste produced	660			
Bio/ Waste imported	70			
Coal Supply	**730**	**789**	-7%	

1b Coal

	IEA [ktoe]	EMA [ktoe]	%dif	Table in EMA 2018 Energy Statistics / Method
Imported Coal	-	426.6		T1.1 Imports of energy products
Exported Coal	-	0.6		T4.2 Natural gas balance
Coal Supply	**430**	**426**	1%	

1c Natural Gas (PNG + LNG)

	IEA [ktoe]	EMA [ktoe]	%dif	Table in EMA 2018 Energy Statistics / Method	
Imported PNG	-	7418.6		T1.1 Imports of energy products	
Imported LNG	-	2261.9		T1.1 Assumed LNG regasification efficiency:	100.0%
Stock Exchange	-	51.6		T4.2 Natural gas balance	
Natural Gas Supply	**8710**	**9732**	-11%		

Natural gas balance			
to Electricity Generation	8364		
to Other Transformations	12		T4.2 Natural gas balance
Statistical Differences	-4		T4.2 Natural gas balance
Total final consumption	1360		
Total demand	9732	0.03	Nat gas balanced

Total supply matches EMA gas balance

1d Crude and Petroleum Products

Definitions for Oil Balance

Demand Analysis

Subsectors	IEA [ktoe]	EMA [ktoe]	%dif	Table in EMA 2018 Energy Statistics / Method
Power generation - Main	130	47.3	6%	T2.1 Energy flows into Electricity Generation
Power generation - Autoproducer		75.5		T2.1
Industry	10670	6554.3	63%	T3.12 Oil consumption by sector
Transpo	2090	2349.0	-11%	T3.12
Commerce + service-related	80	77.3	3%	T3.12
Households	30	25.8	16%	T3.12
Domestic Oil Demand	**13000**	**9129**	42%	IEA industry oil demand contains non-energetic; EMA is inferred to be 100% energetic.
Domestic oil demand w/ AH		**8870**		

Oil Balance / Supply Analysis

	IEA [ktoe]	EMA [ktoe]	%dif	
Crude Im/Ex				
Imported crude	56040	52776	6%	*T1.1 Imports of energy products*
Exported crude	-750	-1026	-27%	*T1.2 Exports of energy products*
Domestic crude supply	**55290**	**51750**	7%	
Refinery inputs				
Crude oil and natural gas liquids		46655		*T2.6 Energy flows into the oil refining sector*
Other feedstock		6650		*T2.6*
Total refinery input	**55290**	**53305**	4%	
Refinery outputs				
Light Distillates		14183		*T2.6*
Middle Distillates		22089		*T2.6*
Heavy Distillates & Residuum		15181		*T2.6*
Total	**53000**	**51453**	3%	

Imports: T1.1 Imports of energy products
Exports: T1.2 Exports of energy products

Petroleum Im/Ex	IEA [ktoe]			EMA [ktoe]		
	Im	**Ex**	**Net Import**	**Im**	**Ex**	**Net Import**
Fuel Oil				68561	30696	37864
Gas/ Diesel Oil				15896	25527	-9631
Gasoline				16891	26082	-9191
Jet Fuel Kerosene				3131	6155	-3024
Naphtha				7222	1106	6115
Other Petroleum Products				1648	8718	-7070
Totals	121380	97560	23820	113348	98284	15064

Net PP import **15064**

Crude and Petroleum Products (PP) Balance

	[ktoe]	
Unrefined crude + NGLs	5095	*May be higher because no number on original NGL supply.*
Unrefined crude + NGLs Stock Draw	142	*T1.3 Stock change*
Net PP import	15064	
Refined PP in SG	51453	
PP Stock Draw	541	*T1.3 Stock change*
PP Bunkering	-54640	*IEA 2016; both for shipping and aviation*
Domestic crude + PP demand	**17654**	
Breakdown via energetic		
Oil demand, energetic	9129	
Non-energetic use of oil	8525	
Breakdown via AH contribution		
Oil demand w/ AH contribution	8870	
Oil demand w/o AH contribution	8784	
Domestic PP demand		*Mauve and gray flux in the Sankey excludes (unrefined) crude.*
PP total demand	12418	
Non-energetic use of PP	3289	
Transpo oil w/o AH	259	
Oil demand w/o AH	3548	

Volume of oil trade in SG

	[Mtoe]
Crude import	52.8
PP import	113.3
Crude export	1.0
PP export	98.3
Total Crude+PP Import	166.1
Total Crude+PP Export	99.3
PP Bunkering	54.6
Domestic, inland oil demand	17.7

Energy Transformation

2a Power Generation

Fuel input to power plants, incl. autoproducers

Fuel	IEA [ktoe]	EMA [ktoe]	%dif	Table in EMA 2018 Energy Statistics / Method
Natural gas	7530	8364.2	-10%	T2.1 Energy flows into Electricity Generation
Waste+Biomass+Others	730	788.6		T2.1
Coal+Peat	260	259.2		T2.1
Oil	130	122.8		T2.1
Total energy input	8650	9534.9	-9%	
Gross electricity produced	4440	4435.6		T2.1
Total electricity end-use	4180	4181.1		T3.2 Electricity consumption by sub-sector
Heat generated by power plants	4210	5099.2	-17%	Calc. - Valid only if all thermal generation
of which cogen		2235.4		
lost heat		2863.8		
Power grid losses + pwr plant own-use	260	254.5		Calc. Also includes any statistical differences, which is treated as losses.
Efficiency of Power Grid	94.1%	94.3%		Calc.
Efficiency of Power Gen + Grid		43.9%		

2b Process heat from cogeneration

Solution

Step 1 - (result) Indicative average electrical load factor

Cogen (PNG+LNG) registered capacity	4137	[MW]
Ave load factors	42%	[%]

Step 2 - Setup cogen efficiency parameters

Electrical efficiency	31%	[%]
Heat-to-power ratio	1.7	[-]
Heat	54%	[%]
Heat and power	85%	[%]

Step 3 - Calculate cogeneration production

	[ktoe]
Electricity	1315
Heat	**2235**

Step 4 - Criticize the result by comparing with refinery energy requirements

	[ktoe]		
Refinery output	51453	Refinery Heat-to-Power	10.11

	low	*high*	
Refining energy requirement	2573	5145	Blok, K. (2006)
of which heat	2341	4682	
of which power	232	463	

Step 1 - Estimate an indicative average electrical load factor for all cogens

CCGT and cogen CCGT stats

	[MW] *All*	*of which cogen*	
Registered Capacity	10341	4137	*Data from CS1.5 power plant database*
PNG plants	5402	1255	
LNG plants	4939	2882	

CCGT efficiency (indicative)

HHV heat rate	7103.8	[BTU/kWh]	*EMA 2016 Vesting Contract Technical Parameters*
Efficiency	48%	[%]	

Electricity produced by natural gas plants (2016)	[ktoe]	
Natural gas	4018	
LNG	1086	*Assume ALL LNG imports are for power*
PNG	2931	

Ave load factors	[%]	
PNG plant	72%	
LNG plant	29%	
Overall	**42%**	*Weighted by cogen capacity*

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End-Use

3a-c Industry, Buildings and Transportation

EMA data T3.13 Total final energy consumption

*Town gas is bundled with natural gas.
**No data for process heat demand; high estimate of cogen process heat assigned to Industry

Sector	Consumption by carrier	[ktoe]	
3a Industry	[ktoe]		
	electricity	1756	
	oil products	6554	
	natural gas	1193	
	coal	167	
	process heat	2235	Estimate (see 2b)

Sector	Carrier	[ktoe]
3b Commerce+Services	[ktoe]	
	electricity	1522
	oil products	77
	natural gas	92
	coal	-
	process heat	-
Households	[ktoe]	
	electricity	653
	oil products	26
	natural gas	61
	coal	-
	process heat	-

Buildings (Commerce+Services+Households)

Carrier	[ktoe]
electricity	2174
oil products	103
natural gas	153
coal	-
process heat	-

Sector	Carrier	[ktoe]			
Others	[ktoe]				
	electricity	24			
	oil products	-			
	natural gas	3			
	coal	-			
	process heat	-			
3c Transport	[ktoe]				
	electricity	227			
	oil products	2349	of which for road:	2090	based on IEA data for 2016
	natural gas	11			
	coal	-			
	process heat	-			

EMA Total Final Consumption [ktoe]

[ktoe]	
electricity	4181
oil products	9006
natural gas	1360
coal	167
process heat	2235
Total	**16950**

Anthropogenic Heat

4a Metabolism

Human Metabolism is estimated based on average human heat gains (W), and calculated annually for the population of Singapore

Back of the envelope calculation

Ave. human heat gains	137	[W/person]	*Source : Diurnal and weekly variation of anthropogenic heat emissions in a tropical city, Singapore. (Anne K., L. Quah, Matthias Roth; 2011)*
Annual heat per person	1.03E-04	[ktoe/yr-person]	*Calc.*
SG population	5607283	[person]	SingStat
Total AH metabolism	579	[ktoe/yr]	*Calc.*

4b ***AH sources per sector*** *(electricity AH NOT allocated)*

By source	[ktoe]	[%]
Power plants (excl. cogen)	2864	14.1%
Power grid	255	1.2%
Power plants and grid	3118	15.3%
Industry (incl. cogen)	11906	58.5%
Buildings	2430	11.9%
Transport	2328	11.4%
Human Metabolism	579	2.8%
Total	**20362**	

Ignoring absorbed energy

4c ***AH sources per sector with electricity heat allocation***

	[ktoe] Elect. consumption	weight	[ktoe] Electricity AH allocation	% Total AH
To industry	1756	0.42	1317	6%
To buildings	2174	0.52	1631	8%
To transpo	227	0.05	170	1%
Total	4157			

Sector AH with electricity heat allocation

	[ktoe]	
Industry	13223	64.9%
Buildings	4062	19.9%
Transpo	2498	12.3%
Human Metabolism	579	2.8%
Total	**20362**	

- End of Sheet -

Annex C – Simple example analyses with the Sankey

In this annex, we provide two simple scenario descriptions as examples on how to conduct analyses with the Sankey diagram.

Maximizing the PV potential in Singapore

The authors of (Luther & Reindl, 2014) formulated annual PV production under normal and accelerated deployment scenarios. As a quick estimate of how PV adoption would change the heat emissions of buildings, we follow these steps:

1. As the baseline, use the 2016 electricity consumption, direct and indirect heat of *Buildings*.
2. Using the maximum PV generation (accelerated scenario), calculate the remaining electricity demand (grid demand).
3. Calculate the indirect heat by scaling the 2016 value by the reduction in the grid demand.
4. The direct heat remains the same, as there is no change in consumption behavior.

The results of this analysis is shown in Figure 4. If the 2030 PV production potential was achieved in 2016, the grid demand would be down to 66% of the baseline, with a reduction of indirect heat from electricity by **553 ktoe** (down 34% of the electricity indirect heat or 2.72% of Singapore's total AH in 2016).

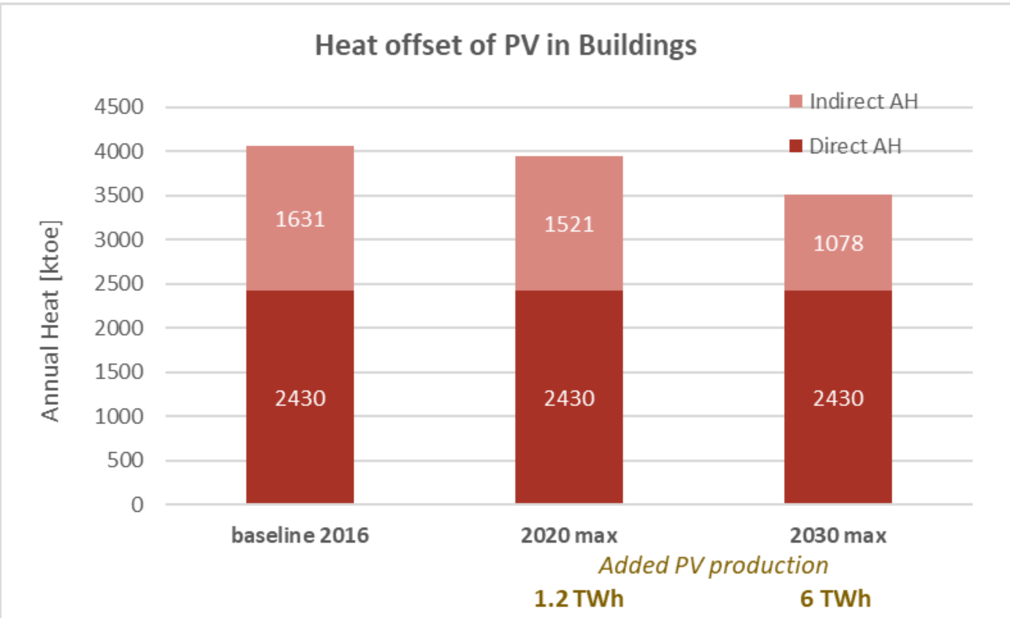

Figure 4 Heat offset of PV in Buildings

Equivalent heat improvements (i.e. reduction of indirect heat) can also be met by thermal improvements of Singapore's electricity. However, if building efficiency and consumption patterns were improved, then *both* direct and indirect heat would be reduced.

Electrification of all road transport

In the hypothetical scenario that all road transport in Singapore is electrified, the effects on the Sankey diagram would occur in two places. First, the total amount of energy used for road transport, and therefore the heat released on the roads, would be reduced. EVs are in general three times more efficient than ICE vehicles. Second, the electricity indirect heat released by transportation would increase, owing to the energy shift. There would be a significant displacement of the released heat from the roads to the power stations, and the overall change in heat depends on the efficiencies along the energy chain (i.e. EV vs. ICE vehicles and power stations) and other factors (i.e. any possible changes in driving patterns, and how much of the power stations is thermal).

We can make a quick estimate of this scenario in Singapore as follows:

1. Assuming no change in driving patterns, a fully electrified road transportation would consume about a third of 2090 ktoe, or **697 ktoe of electricity**.

2. The average efficiency of the power sector is 43.9%. Assuming this holds for the added electricity demand, and that only thermal generation is activated, an additional (697 ktoe / 43.9%) = 1587 ktoe of fuel is input to power plants.

3. The power sector thus releases an additional 1587 ktoe - 697 ktoe = **+890 ktoe of heat**.

4. The transport sector heat release changes by -2090 ktoe + 697 ktoe = **-1393 ktoe of heat**.

5. Overall, Singapore releases **503 ktoe *less* heat** (down 2.47%).

Even though we have a positive effect on the total AH released with full electrification of road transport, we still need to conduct mesoscale analyses to verify this positive effect to the UHI and OTC. It is worth noting that transport electrification has plenty of effects other than heat, such as other emissions (CO_2, NOx, particulate matter) and possible changes in driving patterns.

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