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Effects of Sustainable Energy Supply on Global Transportation Hubs

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1 Abstract

This study investigates the feasibility of a renewable energy supply for hub cities and discusses the resulting impact of sustainable supply concepts on international transportation.

Whereas renewable energy potentials are highly dependent on geographical circumstances and limited by regional availability, formation of hub cities leads to very high local energy demands caused by their specializations. Especially air and marine transportation require huge amounts of energy. A shift in energy supply can lead to significant changes in transport costs and therefore threat the current business model of hub cities. These developments are discussed on basis of Singapore and assessed by a comparison with a federal structured system.

Singapore is one of the world's largest hubs for marine bunkering and aviation. A detailed analysis of Singapore's energy systems shows the significant impact of hub specializations on its energy demand. Conventional fuels for international transportation are analyzed and future developments are predicted. In different scenarios these amounts are substituted by the alternative fuels biofuel, LNG and hydrogen. Possible reductions of carbon emissions are shown. Regional and global production and potentials of these fuels are opposed to resulting demands. In addition to these energetic investigations also economic and ecologic aspects are examined. The influences of the resulting transport costs on Singapore's role as a transportation hub are discussed and compared to effects on a federal structured system in different countries. Risks and opportunities for Singapore's role as a sustainable global transportation hub are highlighted in respect of global trends in climate change mitigation.

2 Introduction

Supply of global hub cities with sustainable energy will become one of the biggest challenges within the worldwide trend to substitute fossil fuels.

This results from two contrary characteristics:

- Limitation of renewable energy potential by geography and space
- Very high energy demand of hubs at a single regional location

Renewable energy potentials are limited and highly dependent on geographical circumstances. Sources like wind, solar, hydro and biomass have a maximum power density per unit land area. In contrast to positive effects of scale in economics, renewable energy production shows negative effects of scale as suitable locations are used in particular. With rising generation capacities also less suitable sites are utilized for energy production.

Urbanization and economic advantages result in a strong growth of hub cities. Big parts of their energy consumption are caused by specialization effects, as hubs do not only provide their services to their own population but also in a countrywide or global scale. This causes a very high energy demand on a single regional location.

Today, energy demands of hubs are mainly supplied by import of fossil fuels, which are characterized by very high power densities and an excellent transportability. Limited availability of fossil fuels, volatile commodity markets, negative environmental effects and steadily improving technologies for harvesting renewable energies caused a global trend to substitute conventional fuels in the long term. Hubs offering services to global partners have to cover these changing demands.

Singapore is such a hub city. It is one of the largest exporting refinery centers [1]. In 2012, 83.8 megatons of oil equivalent (Mtoe) petroleum products were refined or traded for export [2]. With 31 million Twenty-foot Equivalent Units (TEUs) of container traffic in 2012, Singapore is one of world’s busiest container ports. 43 million tons of bunker sales make Singapore to world’s top bunkering port.[3] Changi airport, Singapore’s international airport, serviced over 51.9 million passengers in 2012 [4].

In the long term, Singapore must consider options to transform its energy system in order to keep its dominant position in international transport und energy. This will affect its competitiveness and its future position in the transport network.

This paper analyses the amount of energy which has to be supplied in a sustainable way and shows options how this can be achieved. The effects are discussed on basis of a comparison with more federal structures in other countries.

3 Methodology

Profound understanding of existing structures and a detailed analysis of the current energy use and demand is mandatory to investigate the feasibility of a sustainable energy supply based on renewable energy carriers. Figure 1 displays the general methodology.

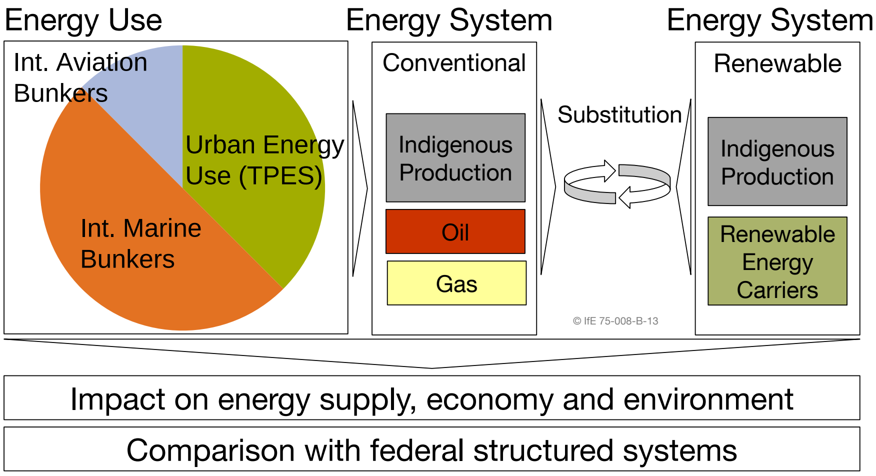

Figure 1: Analysis of energy use and supply

In a first step primary energy imports and indigenous production are analyzed by type and quantity. These are distributed to the different consumers. Usually four consumption sectors are distinguished: Households or Residential, Commercial, Industry and Transportation. These sectors only cover urban use of energy. Energy demand of global transportation hubs is not only depending on domestic energy consumption, but also on fuels supplied to ships and airplanes. These fuels, so called international bunkers, can increase overall energy consumption significantly.

Data about energy consumption can be derived from studies of different organizations. International Energy Agency (IEA), Energy Information Authority (EIA), BP plc. and governmental organizations publish energy balances for countries' energy use.

The amount of bunker fuels is converted into energy by appropriate conversion factors.

These amounts have to be covered by renewable energy supply. Different fuel types and technologies are discussed to substitute conventional energy carriers. In addition to the carbon free energy carrier hydrogen, biofuels and LNG as a prospective fuel for marine transportation are investigated. Local, regional and global alternative energy potentials are opposed to required energy amounts.

Current energy demand, technology improvements and costs are included in the investigation. Extreme scenarios which assume a total substitution of conventional energy carriers are discussed to cover a broad range of different developments. The impact of hub effects is compared to federal structures. Outcomes are assessed to show the impact of hub systems on local energy demand and resulting consequences for a sustainable energy supply.

4 Results and Discussions

Energy demand and supply by conventional energy carriers

Energy balances describe energy imports, indigenous energy production, energy exports, international marine bunkers, international aviation bunkers and stock changes. The definition of primary energy demand in a country varies in different studies. While Energy Information Authority (EIA) and British Petroleum (BP) account international bunkers to primary energy demand, the International Energy Agency (IEA) distinguishes between Total Primary Energy Supply (TPES) and international bunker fuels [1, 5, 6].

Table 1 gives an overview about primary energy demand including international marine and aviation bunkers to Singapore from 2006 to 2011 according to different organizations. Energy use is defined as primary energy production and imports reduced by energy exports. It can be seen that statistics vary.

Table 1: Primary Energy Use [Mtoe] in Singapore including international bunkers from 2006 to 2011

Institution	Unit	2006	2007	2008	2009	2010	2011
SG Energy Market Authority*[2]	Mtoe	54.9	54.6	59.2	62.3	65.6	66.0
U.S. Energy Information Authority**[7]	Mtoe	52.5	57.0	62.0	72.9	85.0	72.2
BP British Petroleum**[1]	Mtoe	53.0	58.4	61.2	64.5	70.6	73.7
IEA International Energy Agency**[6]	Mtoe	55.2	57.8	64.5	69.8	79.2	79.9

* information about international bunkers not available

** including international marine and aviation bunkers

International Energy Agency gives the most subdivided statistical data about energy consumption. Therefore these data are used in the study. Figure 2 visualizes primary energy supply and use in Singapore based on IEA figured.

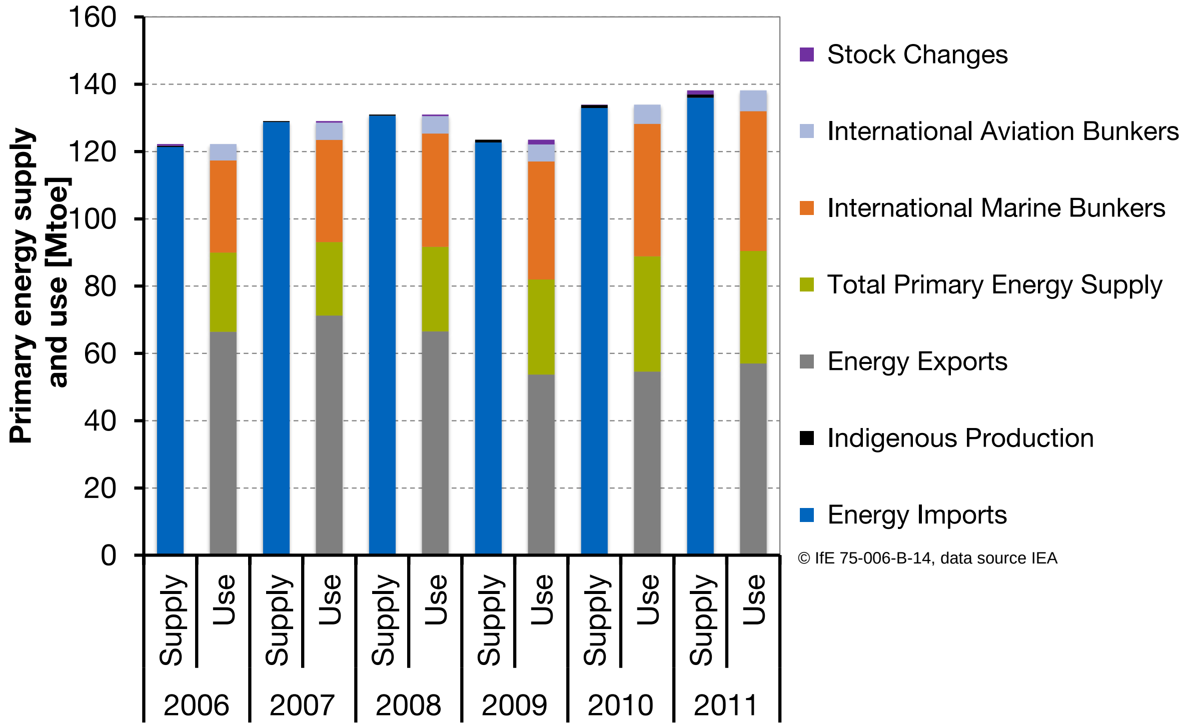

Figure 2: Influence of marine transportation and aviation on Singapore's net energy imports

As indigenous production in Singapore is very low (< 1Mtoe [6]), primary energy supply in Singapore is determined by energy imports. Changes in energy stock have only a limited impact. The largest share of imported energy is exported after refining or trading. Energy used in Singapore can be split up into two categories:

- Use for domestic energy demand (Total Primary Energy Supply)
- Use for international energy demand (International Marine Bunkers and International Aviation bunkers)

Domestic energy use rose from 23.5 Mtoe in 2006 to 33.5 Mtoe in 2011. International marine bunkers have been growing from 27.4 Mtoe to 41.6 Mtoe in the same period. Demand of aviation bunkers increased from 4.9 Mtoe to 6.2 Mtoe.[6] Singapore's energy use for international transportation has been significantly higher than its domestic energy demand. In order to keep its dominant position as a transportation and energy hub in the long term, Singapore needs to develop a sustainable energy strategy also for international purposes. In the next section options for alternative energy carriers in transportation are discussed.

Unconventional energy carriers for transport use

Fuel mix of international marine and air transportation is highly dominated by fossil fuels. In marine transport marine fuel oil (MFO) is used for propulsion. For auxiliary engines and operation in harbors marine gas oil (MGO) or marine diesel oil (MDO) is bunkered. The share of MGO/MDO on total bunker fuels in Singapore declined from 6 % in 2005 to 3 % in 2012 [3]. Liquefied natural gas (LNG) is applied for some special purposes like LNG transport and ferry operation.[8]

In this study all bunker fuels are treated as one fuel type dominated by MFO. In the aviation industry kerosene and jet fuels dominate the fuel mix, due to high requirements concerning fuel quality. In the following LNG, biofuels and hydrogen, as a long-term alternative, are further investigated.

Biofuels can be refined from different biomass sources and used for different purposes. MFO could be substituted by vegetable oil. Biofuels can substitute middle distillates MGO and MDO.[8] Recent tests with high blends of biofuels showed that technically biofuels could substitute conventional jet fuel [9]. Therefore, biofuels can be used in aviation and maritime transport. To substitute conventional fuels, different kinds of biofuels have to be assumed. Table 2 gives an overview about energetic indicators of vegetable oil as substitute to MFO, bio diesel as substitute to MGO/MDO and bio-derived jet fuel as substitute to jet fuels. Factors are used to convert units from different international sources into common units.

Table 2: Overview about energetic indicators of biofuels for transportation purposes [8, 9]

Bio Fuel Type	vegetable oil	bio diesel	bio-derived jet fuel
Calorific value	37 MJ/kg	37.5 MJ/kg	42.8 MJ/kg
Density 15 °C	920-960 kg/m³	860-900 kg/m³	775-840 kg/m³

Vegetable oil is the least upgraded product, which is extracted from plants. Worldwide production accounted for 170 million metric tons in 2013. This consists of 59.3 million metric tons from palm, 45.0 million metric tons from soybean, 26.0 million metric tons from rapeseed, 15.5 million metric tons from sunflowerseed and 24.2 million tons from other sources.[10] Only a minor share of this amount is used for production of bio fuels. Bio diesel is based on refined vegetable oil, waste or other biomass. In 2011, global bio diesel production was 403.739 thousand barrels per day, around 20.6 Mtoe [11]. Bio-derived jet fuel can be derived from biomass, waste or natural gas. Recent demonstration flights were carried out with up to 50 % jet fuel blend from natural gas, jatropha, algae or other sources.[9] On global scale biofuels have a positive impact on total emissions compared to conventional fuels as direct carbon emissions are prior consumed by the plants. Additional emissions may occur due to transportation, harvesting and processing. On a local scale carbon emissions remain similar to conventional fuels whereas sulfur emissions are reduced significantly [8].

LNG is an often discussed fuel for future marine transportation. Unlike conventional fuel LNG won't need any exhaust treatment in emission control areas (ECA). LNG has less CO_2 emissions and significantly reduced NO_x emissions. In addition LNG has no sulfur emissions. [8] Prices of LNG differ by region as there is no global gas market. Price differences in the last years reached from under 4 US$/mmBtu in the US to nearly 20 US$/mmBtu in the Asian market [12–14]. LNG is partly cheaper than middle distillate fuel. Global LNG liquefaction capacity in 2012 had a volume of 281 million tons per year [15]. Two gas based aviation fuels are in current discussion: Gas to liquid (GTL) and LNG. While LNG could just be produced by liquefaction of natural gas, GTL is produced in an expensive multi-stage process. This paper will focus on the cheaper but technologically more challenging option of LNG as an aviation fuel.

Hydrogen is often in discussion as a future fuel. Its natural occurrence on earth is always in a bound form in combination with other elements. Multiple pathways for hydrogen production are possible. 50 million tons of hydrogen are produced each year. Most of it by steam reforming and processing of conventional fuels. Only minor shares are produced by electrolysis of water.[16] Hydrogen can be transported and stored in compressed or liquid form. Also other options like absorption storage are possible. Use of hydrogen won't lead to direct emissions besides vapor. Utilization is possible in fuel cells or combustion engines. Indirect use of hydrogen via methanization may be an interesting option to utilize surplus of electricity caused by renewable energy generation when no direct use of hydrogen is feasible. Today prices for hydrogen are high compared to other energy carriers, as hydrogen is generated mainly from conventional energy carriers. Hydrogen causes no local emissions. When hydrogen is supplied by renewable energy carriers carbon emissions for its production are very low.

Effects of total substitution of conventional energy carriers

In order to supply feedstock for biofuel production certain land areas to cultivate oil plants are needed. Oil palms have the highest oil yields with 610 gallons/acre, followed by jatropha with 194 gallons/acre. Other feedstock used for oil production like rapeseed (122 gallons/acre), sunflower (98 gallons/acre) and soybean (46 gallons/acre) reach significantly lower yields. [17]

Algae with yields up to 10,000 gallons/acre [18, 19] could considerably reduce land use for production of vegetable oil. Urban waste is another possible source for oil production. Oil yields vary in a broad range according to its composition.

A total substitution of Singapore's bunker fuels by vegetable oil would not only mean an increase in worldwide consumption of vegetable oil by around 30 % but also huge additional areas under cultivation. Figure 3 shows the required land areas for different feedstock.

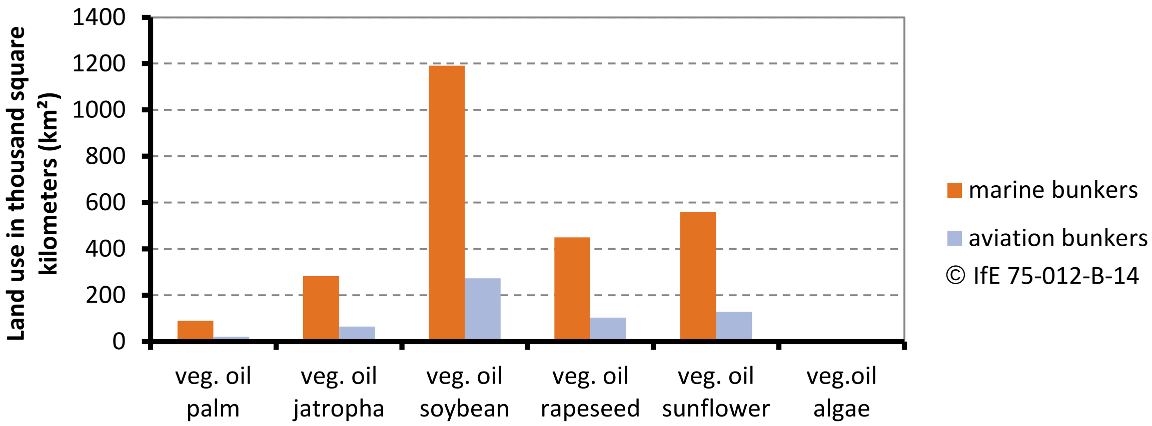

Figure 3: Land use of different feedstock for vegetable oil production in order to supply Singapore's maritime and aviation bunker fuels

As mentioned above all marine bunker fuels are substituted by one fuel type as share of MGO/MDO is small. Land use for substitution with vegetable oil from oil palm would result in a land use of 89,847 km². Jet fuels are substituted by bio-derived jet fuels from palm oil. In this example feedstock are processed in a hydrodeoxygenation process with an efficiency of 65 % [9]. Total land use amounts to 20,579 km².

With all feedstock total land area of Singapore itself is surpassed several hundred times. However, surrounding countries Indonesia and Malaysia are the largest producers of palm oil. Indonesia with a production of 31 million metric tons of palm oil together with Indonesia (production 19.9 million metric tons of palm oil) had a market share of around 86 % in 2012/13 [20]. This whole production would be required in order to supply Singapore's bunker fuels today. Other fuel sources would even mean larger areas for cultivation and higher transport efforts. More effective technologies like algae could lower land use significantly by decreasing the required land area by a factor of 10 compared to palm oil.

LNG is a potential substitute to marine bunkers in the mid term and aviation in the long term. Singapore is to become a major LNG hub in South East Asia. The initial storage capacity of 3.5 million tons per year was expanded to 6 million tons per year [21]. In order to supply today's 41.6 Mtoe bunker fuels around 34.1 million tons of

LNG would be required. Additional 5.1 million tons of LNG would be needed to substitute aviation fuels. 238 million tons of LNG were traded in 2012. Large exporters in the region are Malaysia (23.1 MTPA), Australia (20.8 MTPA) and Indonesia (18.1 MTPA) [15]. Big price differences could lead to a global LNG market and a price reduction in South East Asia.

Hydrogen use in shipping would require huge production capacities. Higher fuel efficiencies have to be considered as combustion engines can be substituted by fuel cells. It is assumed that this results in a reduction in fuel consumption of 17 % compared to conventional combustion engines. On today's basis, this leads to a reduced energy demand of 34.5 Mtoe in liquid hydrogen. Additional energy is needed to transform the hydrogen in a liquid phase for transport and storage. Liquefaction efficiency is set to 75 %. Therefore, energy demand increases to 46.0 Mtoe in hydrogen. Today hydrogen is mainly supplied by steam reforming for ammonia production and industrial processes [16]. In these scenarios hydrogen is used as a transportation fuel. Carbon free hydrogen generation could be achieved by electrolysis. With an efficiency of 70% this results in 65.7 Mtoe electricity needed for hydrogen production. A total supply of marine transport fuels would mean an installed solar capacity of 511 GW assuming 1500 h full load hours. Total land use for such a generation capacity is 16,481 km² with 31 MW solar capacity per km² [22]. Alternatively installed wind capacity would be lower with 192 GW assuming 4000 full load hours. However, a higher specific land use caused by 3 MW wind capacity per km² [23] leads to 63,864 km² required land area. It's important to note that such excellent wind sights are not available in Singapore. To substitute aviation fuels additional 5.1 Mtoe liquid hydrogen are required. With above pathways, required solar capacity would add up to 76 GW (2,454 km²) while required wind capacity would be 29 GW (9,508 km²). It has to be mentioned that total land use does not necessarily mean lost area. Especially alternative land use of wind parks is possible for agricultural purposes.

In any case it becomes clear that Singapore with its total land area of 714,3 km² [24] will not be able to supply its energy requirement by inland energy sources. Future energy carriers have to be imported to Singapore.

Economic impact of alternative transportation fuels

International transport is highly dependent on fuel prices. Substitution of conventional fuels for marine and aviation purposes leads to a change in transportation costs. Higher transportation costs result in shipping of more valuable goods whereas lower transportation costs have the effect of a higher share of goods with lower value [25].

In the following a rough investigation of the impact of alternative transport fuels for marine transportation is conducted to show principal developments. Therefore, the effects on a conventional container ship with a capacity of 10,000 TEUs servicing a shipping route between Singapore and Germany are shown. Fuel consumption is calculated based on carbon emissions in order to cover realistic service behavior including driving behavior and operation in harbors. Container transportation and shipping company CMA CGM publishes a value of 73 g CO_2/TEU-km for their container fleet [26]. An average ship with a total container capacity of 10,000 TEU is assumed. Based on specific emission values a fuel consumption of 0.242 t fuel/km is calculated. Fuel costs of 0.017 USD/TEU-km result when an average bunker price of 700 USD/t fuel is used. Share of fuel costs on total operational costs including crew, maintenance, insurance, administration and others is 45 % for a ship with 10,000 TEU capacity [27]. Total operational costs for transportation of one container from Singapore to Germany are 595 USD based on these assumptions. Effects on these costs, when conventional fuel is substituted with hydrogen, biomass and LNG are shown in Figure 4.

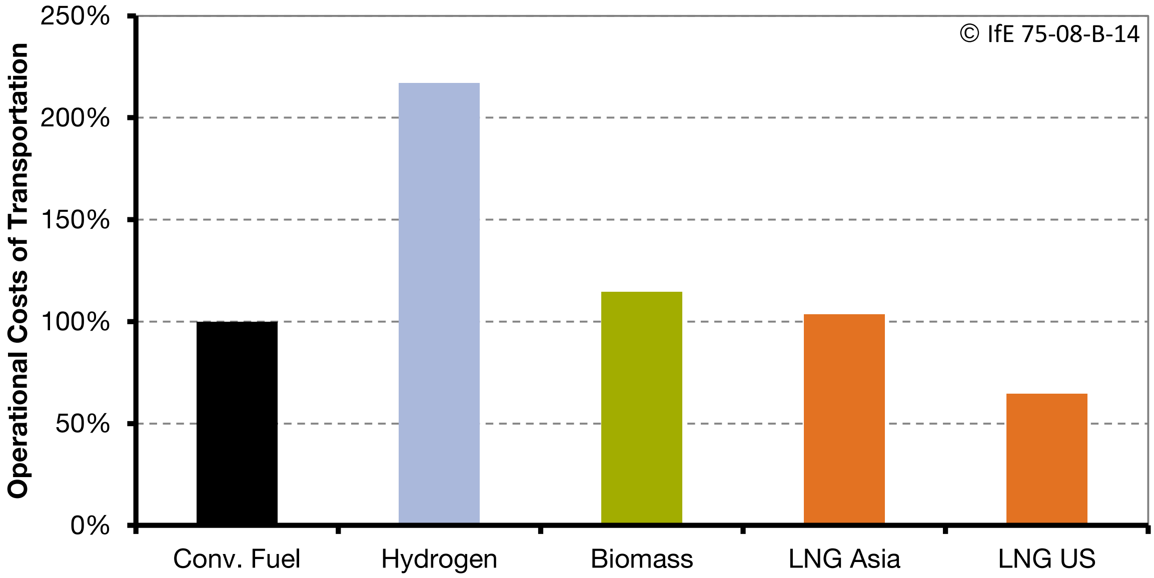

Figure 4: Changes in operational transport costs by substitution with alternative fuels in marine transport

Hydrogen results in the highest costs for transportation (1,292 USD/TEU). 9.11 USD/kg fuel costs are calculated for hydrogen supplied by solar photovoltaics including costs for electrolysis and liquefaction. Costs for biomass based on vegetable oil from palm oil are 15 % higher (683 USD/TEU) than transportation with conventional fuel. This is caused by the higher costs of palm oil (860 USD/t) compared to conventional bunker fuel. LNG is only traded on regional markets. Therefore, prices differ according to different world regions. In Asia LNG prices peaked with nearly 20 USD/mmBtu. Unconventional gas leads to significantly lower LNG prices in the US (4 USD/mmBtu).[12–14] In order to cover this broad range of prices and possible changes both areas were taken into account. LNG prices in Asia would result in a slight increase at around 4 % (617 USD/TEU). LNG prices in the US would even decrease operational transportation costs by 35 % to 385 USD/TEU. This rough calculation shows that impact of higher fuel costs on global transportation is not as high as it might be initially assumed. Especially LNG could not only be a more ecologic but also quite economic option for marine transportation.

Fuel prices were taken in accordance with different sources and set to mirror the situation in 2012 for better consistency. Above calculations imply that drive train costs of different ship types are the same. Actual trends in marine transportation like slow-steaming and reduced fuel consumption, emission control areas (ECAs) and larger container ship capacities can have big influences on the results above. These important factors have to be included in future research.

Comparison to federal structured systems

Finally the economic impact of Singapore's hub structure is analyzed in comparison to more federal structured systems. Figure 5 visualizes the specific primary energy (PE) use per land area together with gross domestic product (GDP) at Purchasing Power Parity (PPP) per unit of primary energy use and PE per capita. Singapore as a typical hub is compared to more federal structured systems in Germany, USA and China. Primary energy use is defined as energy production plus energy imports and reduced by exports, as these are not consumed but only processed and traded like normal goods.

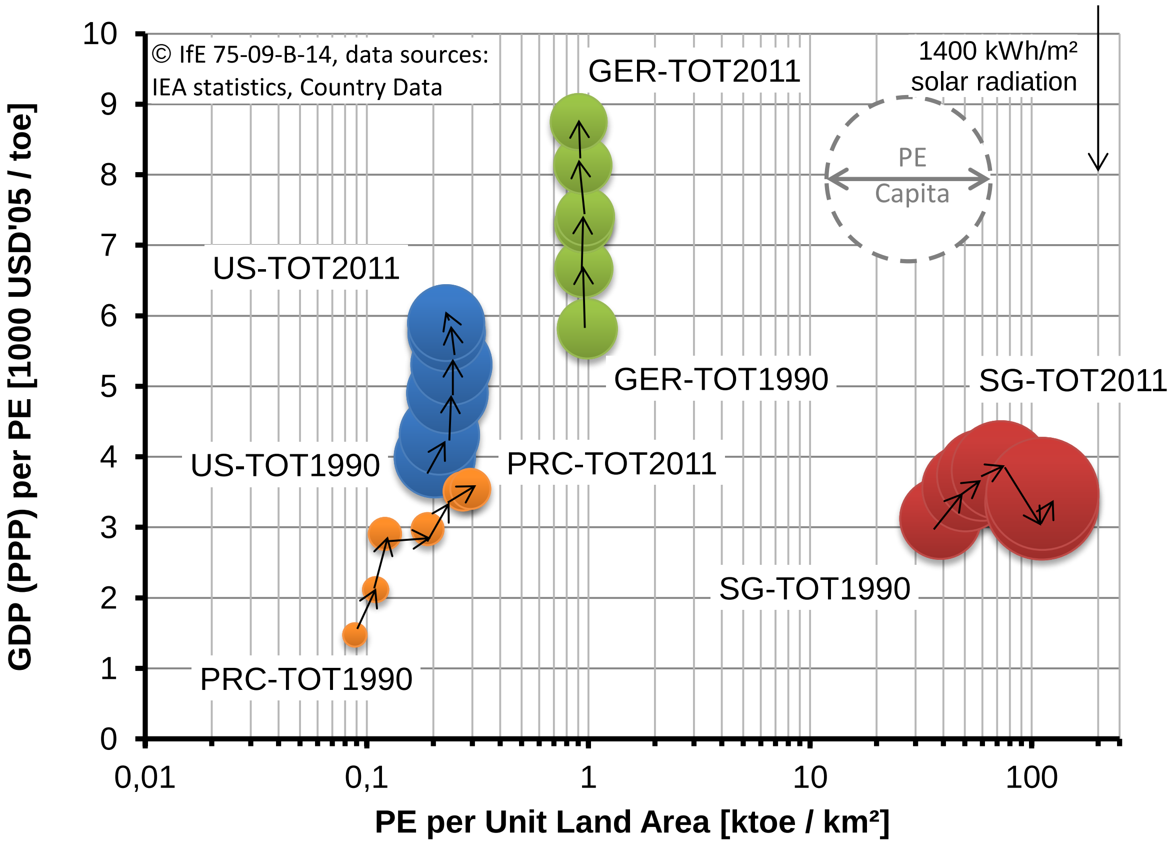

Figure 5: Comparison of specific primary energy consumption per land area and primary energy per capita with GDP (PPP) per unit of primary energy

Primary energy consumption per land area in Singapore is very high and has been rising since 1990 from 38 ktoe/km² to 112 ktoe/km² in 2011. Other countries show a much slower growth (China) or even a decline (Germany and USA). This makes a sustainable energy supply in Singapore much more challenging than in other countries. GDP per unit of energy input is a measure for the efficiency of an economy. In Germany and in the USA an uncoupling of energy consumption and economic performance can be observed whereas Singapore is characterized by a strong coupling of these. China's economic efficiency has been growing more discontinuous due to very high energy demand caused by an extraordinary high economic growth. PE per capita shows the primary energy use per population in the examined countries. Singapore leads this comparison with the highest PE per capita ratio.

5 Conclusion

As analyzed in the previous chapter, impact of transportation on Singapore's overall energy demand is remarkable. Substitution of this demand with locally available alternative energy carriers is not possible. Also renewable energy carriers would have to be imported. Singapore might have positive ecological effects by substituting conventional bunker fuels. Impact on transportation costs is less than expected. However, a final assessment needs further research. A comparison to other countries with a more federal structure shows that Singapore's energy consumption and GDP is strongly coupled. Primary energy consumption per land area is extraordinary high. Summing up sustainable energy supply of Singapore becomes even more challenging when transportation fuels are considered. The multi-hub structure of Singapore results in a very high energy demand. The biggest challenge will be to adapt Singapore's very successful business model to a more sustainable energy supply in order to preserve its international service focus. However, chances to profit from sustainable transportation promise new interesting business options for Singapore.

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