Role of LNG in an optimized hybrid energy network, Part 1 : Balancing renewable energy supply and demand by integration of decentralized LNG regasification with a CHP

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ROLE OF LNG IN AN OPTIMIZED HYBRID ENERGY NETWORK

PART I. Balancing Renewable Energy Supply And Demand By Integration Of Decentralized LNG Regasification With A CHP

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Abstract—The future energy system could benefit from the integration of independent gas, heat and electricity infrastructures. Such a hybrid energy network could support the increase of intermittent renewable energy sources by offering increased operational flexibility. Nowadays, the expectations on Natural Gas resources forecast an increase in the application of Liquefied Natural Gas (LNG), as a means of storage and transportation, which has a high exergy value. Therefore, we analyzed the integration of decentralized LNG regasification with a Waste-to-Energy (W2E) plant for a practice-based case to get an idea on how it might affect the balancing of supply and demand, under optimized exergy efficient conditions. We compared an independent system with an integrated system that consists of the use of the LNG cold to cool the condenser of the W2E plant, as well as the expansion of the regasified LNG in an expander, using a simplified deterministic model based on the energy hub concept. We use the hourly measured electricity and heat demand patterns for 200 households with 35% of the households producing electricity from PV according to a typical measured solar insolation pattern in The Netherlands. The results indicate that the integration affects the imbalance for electricity and heat compared to the independent system. If the electricity demand is met, both the total yearly heat shortage and heat excess are reduced for the integrated system. If the heat demand is met, the total yearly electricity shortage is also reduced (with 100 MWh). However, the total yearly electricity excess is then increased (with 300 MWh). We observed that these changes are solely due to the increase in exergy efficiencies for heat and electricity of the W2E Rankine cycle. The efficiency of the expander is too low to offer a significant contribution to the electricity demand. Therefore, future research should focus on the affect that can be obtained by to other means of integration (e.g. Organic Rankine Cycle and Stirling Cycle).

Keywords—LNG; Cold Recovery; Decentralized Energy Systems; Hybrid Networks; Waste To Energy; Energy Hub; Operational flexibility; Exergy efficiency.

I. INTRODUCTION

Global awareness on energy consumption and the environmental impact of fossil fuels boost actions and create more supportive policies towards sustainable energy

systems. The International Energy Agency (IEA) estimates that, in 2040, 37% of the global electricity generation will come from the renewable wind and solar energy sources [1]. Due to the intermittent nature of these renewable energy sources, this will require an increased operational flexibility of the electricity network [2], which we consider to be the technical ability of a power network to balance the electricity demand and supply in amount over time. For daily and hourly timescales, this can be achieved by cycling (non) thermal units, using energy storage systems and applying demand side management on a central level [3].

On a decentralized level, combining energy infrastructures into a Multi Energy System (MES) or a Hybrid Energy Network (HEN), such as integrating an electricity, gas and district heating network can also provide additional operational flexibility to the electricity network [4][5]. They are already well-known for offering improved energy efficiency in urban areas [6]–[8]. For example, a combined heat and power plant (CHP), that converts primary energy (e.g. biogas or waste) into the energy carriers electricity and heat. Combining the CHP with storage can also provide operational flexibility to the power network [9]. In addition, a HEN can also provide operational flexibility by means of conversion of various energy carriers that offer redundant connections, creating additional degrees of freedom, between the supply and demand[10].

Next to the increase in renewable energy sources, Natural Gas is expected to overtake coal in the global energy mix, with its demand estimated to grow by 50% until 2040 [1]. The integration of the electricity and gas network also offers flexibility to the electricity network, by means of gas turbines, that depends on the gas network flexibility[11]. However, the IEA estimates that the global, long-distance gas trade will be for 53% in the form of Liquefied Natural Gas (LNG). This requires the Natural Gas to be cooled down to around -162°C at atmospheric pressures, so that its volume is reduced with a factor of around 600 [12]. Therefore, LNG is a gas storage that also has a high physical exergy value, which is the maximum amount of work that can be done in a reversible process and represents a

quantification of the usefulness, or quality, of its energy [13]. When the LNG is regasified into Natural Gas, its physical exergy can be exploited by recovering the cold for multiple purposes, such as cooling, nitrogen production, power generation, etc. [12]. Exergy analysis is used to show that the integration of the LNG regasification with medium and small scale CHP systems, by means of using the cold to cool the condenser in the Rankine Cycle [9]-[11], increases the efficiency of a CHP plant. Together with the expansion of the regasified high pressure Natural Gas in a turbine prior to injection into the gas network, the exergy efficiency is significantly increased (1.43 times) for a CHP that uses incineration of biomass or waste [14], [15].

In addition, the expansion of the Natural Gas in a turbine offers a redundant connection between the supply and demand of electricity. This suggests that the integration of decentralized LNG regasification with a CHP might also offer additional operational flexibility to the electricity network. This could allow the LNG regasification to support the increase in intermittent renewable energy sources. However, it would also create an interdependency of the gas, heat and electricity network, where the balancing of the supply and demand of all energy carriers in amount over time is required. The LNG regasification will then not only provide heat to the households, like it does on a central level, but also electricity, which is not produced independently.

To get an idea on how the integration of decentralized LNG regasification with a CHP could affect the balance between the supply and demand of all energy carriers on the future energy network with increased intermittent renewable energy sources, we analyzed a practice-based case. It consists of LNG and waste supply, the decentralized LNG regasification integrated with an existing W2E plant (by means of using the cold to cool the condenser in the Rankine Cycle and expansion of the regasified high pressure Natural Gas in an expander), that provide the (residual) electricity and heat demand for 200 households in the Netherlands, assuming that 35% of the households will have solar PV installed. Under optimized exergy efficient conditions, we analyzed the extent to which the electricity and heat demand were met for every hour of the year, in order to answer the following questions for this case:

- 1) What is the imbalance between the supply and demand for an independent LNG regasification on a central level and the W2E system on a decentralized level?
- 2) How does the decentralized LNG regasification integrated with the W2E system affect the imbalance between the energy supply and demand?

The performance of a HEN can be studied by various concept and evaluation methods [16]. For a decentralized energy system, the energy hub concept is widely used [17] for its design [18] [19] and its operation [20]. It is a representation of the integrated energy network by means of an energy input of production vector P_i of (i) energy carriers, an energy output of load vector L_j of (j) energy carriers and the energy hub that describes the possible energy flow, conversion and storage of multiple energy carriers, by means of a dimensionless Conversion matrix C_{ji} with the efficiencies η_{ji} to convert carrier (i) into carrier (j):

$$L_j = C_{ji} * P_i \quad (1)$$

It allows a range of optimization techniques in terms of (multiple) objectives and approaches [21][22], such as optimal dispatch and optimal power flow in a network [10]. According to this approach multiple energy hubs can also be connected by means of energy transport.

Currently, we report on our analysis of the imbalance for the practise-based case of the decentralized LNG regasification when it is integrated with a W2E plant, for which we applied this energy hub concept. We use typical hourly solar insolation patterns, hourly electricity and heat demand patterns of a household neighbourhood, that were all measured in the Netherlands. The supply of waste and LNG are varied for 2 problem definitions: 1) meeting heat demand and freely producing electricity and 2) meeting electricity demand and freely producing heat.

In the future, we intend to include the logistics related to decentralized LNG, which determine the change in LNG composition due to boil off losses (unwanted regasification) that depend on the surrounding temperature and the transportation time, as well as taking into account the variability and randomness in the different parameters. This requires an extension of the modelling approach and optimization formulation.

In the next section, we describe the integrated LNG regasification and W2E plant systems and the energy hub concept model, as well as the hourly supply and demand patterns, averaged over the month. In the 3rd section, we show the results for the imbalance between the supply and demand and how this is affected by the integration. In the 4th section, we discuss our results on the basis of which we draw conclusions and make suggestions for further research in the final section.

II. METHODOLOGY

To analyse whether decentralized LNG regasification integrated with a W2E plant affects the imbalance between the supply and demand, we modeled the energy network as an energy balance problem, using the energy hub concept.

A. The Energy System

The existing W2E plant in the Netherlands incinerates on average 2200 tons/day of residual waste, to produce steam in the boiler that is expanded in the steam turbine, generating typically 550 kWh electricity/ton at an efficiency of 15%, after which the steam is cooled down in the condenser (HX). They are interested in supplying their waste heat (low exergy) at an efficiency of 73% to meet the heat demand pattern of nearby neighbourhoods (typically 200 households), which is currently met by combustion of Natural Gas from the national gas network. It is integrated with a typical decentralized LNG regasification plant that regasifies 60 to 800 ton of LNG/day[23]. For the integration, it is assumed that the LNG cold is cooling the condenser in the W2E Rankine cycle, which increases the W2E plant efficiency to 25% and 83% for electricity and low exergy heat, respectively

(See Fig.1 based on [14]). In addition, a redundant connection to meet with the electricity demand is offered by expansion of the high pressure Natural Gas in an expander.

Fig. 1. The decentralized LNG regasification integrated with the W2E plant (Based on [14]).

The energy system, which we assumed to be an isolated decentralized network, is represented by a steady state, deterministic, linear programming energy balance problem in Matlab, which is solved by optimizing exergy efficiency. Its main conversion components are (See Fig.2):

- 1) W2E plant for waste into electricity and low exergy heat
- 2) Expander for Natural Gas pressure difference into electricity
- 3) High efficiency boiler for Natural Gas into low exergy heat

The electricity production by the expander (P_{expander}) depends on the mass flow going in and the enthalpy drop over the expander ($\Delta h = 35 \text{ kJ/kg}$). The mass flow is assumed to be the Natural Gas energy flow (P_{LNG}) divided by its Lower Heating Value (LHV = 50,000 kJ/kg), which leads to a contribution that could be negligibly small without additional heating of the Natural Gas, according to:

$$P_{\text{expander}} = \frac{P_{\text{LNG}}}{\text{LHV}} * \Delta h \quad (2)$$

A unidirectional energy flow is assumed from the input to the output. For 2 problem definitions: 1) meeting heat demand and freely producing electricity and 2) meeting electricity demand and freely producing heat, we analysed the extent to which the demands are met. This is compared to the extent to which the demands are met for the analysis of independent LNG regasification on a central level and the W2E plant on a decentralized level that is represented by discarding the expander and reducing the efficiency of the Rankine cycle.

Fig. 2. The energy system modelled as an energy balance problem using the energy hub concept.

The hourly residual electricity and heat demand patterns for the neighbourhood of 200 households are fixed (See Fig.3). They are based on hourly demand measurements for households in the city of Groningen, The Netherlands in 2012, with the yearly average household demand in The Netherlands taken as 4380 kWh/year and 14.06 MWh/year for electricity and heat, respectively [24]. Prior to the analysis, the electricity demand pattern is corrected for the hourly solar electricity production, based on 10 year averaged solar insolation measurements at Eelde, The Netherlands. Therefore, we assume that 35% of the households will have solar PV panels installed. In addition, the heat demand pattern is first corrected for 15% energy savings as a result of installed insulation. The waste and LNG supply can vary unlimited to meet with the hourly demand.

Fig. 3. Hourly residual electricity (L_E) and heat (L_Q) demand patterns summed up per month.

B. The Energy Balance Problem

The decentralized LNG regasification integrated with, or independent from, the W2E plant is represented by the energy input vector $P_i = (P_W, P_{\text{LNG}})$, the Load vector $L_j = (L_E, L_Q)$ and the Conversion matrix C_{ji} , as follows:

$$\begin{bmatrix} L_E \\ L_Q \end{bmatrix} = \begin{bmatrix} \eta_{WE} + a * \eta_{WECold} & a * \eta_{LNGE} \\ \eta_{WQ} + a * \eta_{WQCold} & \eta_{LNGQ} \end{bmatrix} * \begin{bmatrix} P_W \\ P_{LNG} \end{bmatrix} \quad (3)$$

Where:

L_E = electricity demand [kWh]

L_Q = low exergy heat demand [kWh]

P_W = waste supply [kWh]

P_{LNG} = LNG supply [kWh]

a is the integer value, that indicates if the energy system is analyzed with the LNG regasification and W2E plant operating in an integrated ($a=1$) or an independent ($a=0$) way.

η_{WE} = electric efficiency of the W2E plant (15%)

η_{WECold} = increase in electrical efficiency due to the cold recovery (10%).

η_{WQ} = thermal efficiency of the W2E plant (73%)

η_{WQCold} = the increase in thermal efficiency due to the cold recovery (10%).

η_{LNGE} = efficiency of the gas expander (0.07%)

η_{LNGQ} = high efficiency gas boiler efficiency (90%)

The problem is solved by obtaining the input vector, under the requirement of an optimized exergy efficiency for every hour of the year (η_{EX}). This exergy efficiency is defined as the exergy of the energy output in the form of electricity (B_E) and low exergy heat (B_Q) divided by the exergy of the energy input of the waste (B_W), and the LNG based on its LHV (B_{LNG}) and the cold (B_C). Note that the latter is only included for the integrated system ($a=1$):

$$\eta_{EX} = \frac{B_E + B_Q}{B_W + B_{LNG} + a * B_C} \quad (4)$$

The exergy of electricity carrier (B_E) and chemical carriers (B_W and B_{LNG}) are considered to be approximately equal to their power flows L_E , P_W and P_{LNG} [kWh], respectively. The exergy of the heat carrier (B_Q) is its heat flow L_Q multiplied by a coefficient based on its temperature T_Q ($= 313 K$), with respect to a reference temperature ($T_{ref} = 298 K$). When the LNG is regasified to 20 °C, theoretically, an amount of heat (Q) of 830 kJ/kg could be recovered [25]. Based on this, the exergy of the cold carrier (B_C) is obtained from the exergy decrease of the LNG over the heat exchanger (HX), which leads to:

$$B_C = \frac{P_{LNG}}{LHV} * Q * \left(1 - \frac{T_{ref}}{T_{C,LM}} \right) \quad (5)$$

Where $T_{C,LM}$ ($=189 K$) is the logarithmic mean temperature for the LNG cold stream with respect to a reference temperature ($T_{ref} = 298 K$).

Objective function

The exergy output is fixed for every hour on the basis of the residual electricity and heat demand patterns. Therefore, the objective function minimizes the exergy input to optimize the exergy efficiency:

$$\begin{aligned} \text{Min } F, F = P_W + P_{LNG} + a * \frac{P_{LNG}}{LHV} * Q * \\ \left(1 - \frac{T_{ref}}{T_{C,LM}} \right) \end{aligned} \quad (6)$$

Problem variables:

The problem is solved by obtaining the input vector:

P_i [kWh]

Description of the Constraints:

The problem is solved following:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} P_W \\ P_{LNG} \end{bmatrix} \leq \begin{bmatrix} 5500 \\ 1500 \end{bmatrix} \quad (7)$$

$$\eta_{WE} * P_W = 153.3 \quad (8)$$

$$\eta_{WQ} * P_W = 4000 \quad (9)$$

Where:

Eq. (7) = range for the input vector of the system [kWh].

Eq. (8) = electric capacity of the W2E plant [kWh].

Eq. (9) = low exergy heat capacity of the W2E plant [kWh].

For the 2 problem definitions: 1) meeting heat demand and freely producing electricity and 2) meeting electricity demand and freely producing heat, we used, respectively:

$$L_Q = (\eta_{WQ} + a * \eta_{WQCold}) * P_W + (\eta_{LNGQ}) * P_{LNG} \quad (10)$$

$$L_E = (\eta_{WE} + a * \eta_{WECold}) * P_W + (a * \eta_{LNGE}) * P_{LNG} \quad (11)$$

C. Operational flexibility

We use the imbalance between the household demand and the actual production as a measure of operational flexibility of the energy system. For the 2 problem definitions: 1) meeting heat demand, this is the electricity demand (L_E) minus the electricity produced, 2) meeting electricity demand, this is the heat demand (L_Q) minus the heat produced.

Hence, a negative (positive) imbalance indicates the energy system suffers from a shortage (excess) of the energy carrier, denoted by S (Exs) in the results section. The energy system is

considered to be in balance if the imbalance is between ± 0.1 kWh tolerance levels.

III. RESULTS

To determine whether decentralized LNG regasification integrated with a W2E plant affects the imbalance between the supply and demand for this case, we calculated the difference between the residual demand and actual production for the 2 problem definitions.

A. Problem definition 1: Meeting Heat Demand

A comparison between the imbalance obtained from the analysis of the independent and integrated systems on a monthly basis is shown in figure 4. For both systems, the power imbalance strongly varies over the year. During the winter months (Nov, Dec, Jan, Feb), there is an electricity excess, which gradually changes into a power shortage during the summer months (Jun, Jul, Aug, Sep). This is to be expected due to the large variation in seasonal heat demand in The Netherlands, while the residual electricity demand remains relatively constant.

We observe that the electricity excess is increased for the integrated system compared to the independent system. The maximum change in imbalance occurs in February (from 53 MWh for the independent system to 130 MWh for the integrated system). Whereas, the electricity shortage is decreased for the integrated system compared to the independent system.

Fig. 4. The power imbalance for 1) meeting heat demand shows the Shortage (S) and Excess (Exs) for the independent (o) and integrated (i) system.

This is a consequence of the increase in the W2E plant efficiency because of the cold recovery in the condenser. To produce the same amount of heat, the integrated system requires less waste and LNG input, but the electricity output (L_E) will increase due to an efficiency increase that is relatively large for electricity compared to heat. Together with the significantly higher heat over electricity demand during the winter months

(See Fig.3.), this causes the variation in difference in the change in electricity excess and shortage.

B. Problem definition 2: Meeting Electricity Demand

Figure 5 shows the results for the heat imbalance, throughout the year on a monthly basis. The heat imbalance also strongly varies over the year.

Fig. 5. The heat imbalance for 2) meeting electricity demand shows the Shortage (S) and Excess (Exs) for the independent (o) and integrated (i) system.

For both the independent and integrated system, the heat shortages are considerable during the winter months, with the maximum shortage in February of around 264 MWh and 195 MWh, respectively. The excess of heat, which occurs during the summer months, reaches maximum values of around 150 MWh and 98 MWh, for the independent and integrated systems, respectively. This is due to the relatively constant electricity demand over the year, while the yearly heat demand shows a strong seasonal variation.

In general, the integration of decentralized LNG regasification with the W2E plant reduces the imbalance for both the shortage and excess of heat. Again, the reduction is a consequence of the increase in the W2E plant efficiency because of the LNG cold recovery in the condenser. To produce the same amount of electricity, the integrated system requires less waste and LNG input, but the heat output (L_Q) will decrease due to an efficiency increase that is relatively small for heat compared to electricity. The difference between winter and summer is again due to the variation in the seasonal heat demand.

IV. DISCUSSION

The integration of the decentralized LNG regasification with a W2E plant offers an increase in the energy efficiency of 10 % [14]. Because of this efficiency increase, the fixed heat demand (Problem definition 1) is met by a smaller supply of waste and LNG. This also affects the electricity production, which is coupled to the heat production for a CHP. However, because the

increase in efficiency for the electricity production is relatively large compared to that for the heat production, we observe an increase in the excess of electricity and a reduction in the shortage of electricity.

For meeting the fixed electricity demand (Problem definition 2), the increase in energy efficiency results also in a reduced supply of waste and LNG. This also affects the heat production. However, because the increase in efficiency for the heat production is relatively small compared to that for the electricity production, both the shortage and excess of heat are reduced for the integrated system.

However, the overall reduction of the imbalance in produced electricity and residual demand, which we use as a measure for the increase in operational flexibility, is not found for the integrated system compared to the independent one. This is due to the low efficiency of the expander, which leads to a contribution in the electricity production that is negligible compared to the electricity demand. Therefore, it does not offer the redundant path to meet the residual electricity demand that is required to increase the operational flexibility.

V. CONCLUSIONS AND FURTHER RESEARCH

To get an idea on how the integration of decentralized LNG regasification with a CHP could affect the balance between the supply and demand of all energy carriers on the future energy network with increased intermittent renewable energy sources, we analyzed a practice-based case. It consisted of LNG and waste supply, the decentralized LNG regasification integrated with an existing W2E plant (by means of using the cold to cool the condenser in the Rankine Cycle and expansion of the regasified high pressure Natural Gas in an expander), that provides the residual electricity and heat demand for 200 households in the Netherlands. We assumed that 35% of the households will have solar PV installed and 15% energy savings will be realized by installation of insulation. By analyzing, under optimized exergy efficient conditions, the extent to which the electricity and heat demand were met for every hour of the year, we found the following answers to our questions:

1) The imbalance between the supply and demand for an independent LNG regasification on a central level and the W2E system on a decentralized level varies over the year due to the seasonal variation in heat demand. If the heat demand is met (problem definition 1), the total yearly power imbalance consists of a shortage of around 250 MWh and an excess of 150 MWh. If the power demand is met (problem definition 2), the total yearly heat imbalance consists of a shortage of 850 MWh and an excess of 900 MWh.

2) For the decentralized LNG regasification integrated with the W2E system, the imbalance between the energy supply and demand still varies over the year. However, if the heat demand is met (problem definition 1), in general, the total yearly power shortage is reduced to around 150 MWh and the total yearly power excess is increased to 450 MWh. If the power demand is met (problem definition 2), in general, the total yearly heat shortage is reduced to 550 MWh and the total yearly heat excess is reduced to 500 MWh.

Hence, the integration of decentralized LNG regasification with a CHP does not offer an increase in the operation flexibility of the electricity network for this case. However, the change in the imbalance is solely caused by the increase in the exergy efficiency of the W2E Rankine cycle for the integrated system. The efficiency of the gas expander is so low that it does not offer a significant redundant path to meet with the electricity demand. Therefore, we cannot get an idea on how the integrated LNG regasification with the W2E plant could affect the operational flexibility of the energy system from this analysis. In the near future, we will investigate other forms of integration (e.g. Organic Rankine Cycle and Stirling Cycle) because these could offer significant redundant paths to meet with the electricity demand.

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REFERENCES

- [1] (International Energy Agency) IEA, "World Energy Outlook 2016," *OECD/IEA, Paris*, 2016.
- [2] M. Huber, D. Dimkova, and T. Hamacher, "Integration of wind and solar power in Europe: Assessment of flexibility requirements," *Energy*, vol. 69, pp. 236–246, 2014.
- [3] M. I. Alizadeh, M. Parsa Moghaddam, N. Amjadi, P. Siano, and M. K. Sheikh-El-Eslami, "Flexibility in future power systems with high renewable penetration: A review," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 1186–1193, 2016.
- [4] M. Geidl, G. Koepfel, P. Favre-Perrod, B. Klöckl, G. Andersson, and K. Fröhlich, "Energy hubs for the future," *IEEE Power Energy Mag.*, vol. 5, no. 1, pp. 24–30, 2007.
- [5] Z. C. Jinghua Lia, Jiakun Fangb, Qing Zengb, "Optimal Operation of the Integrated Electrical and Heating Systems to Accommodate the Intermittent Renewable Sources.," *Appl. Energy*, vol. Volume 167, no. 1 April 2016, pp. 244–254, 2016.
- [6] S. Fazlollahi, G. Becker, and F. Maréchal, "Multi-objectives, multi-period optimization of district energy systems: III. Distribution networks," *Comput. Chem. Eng.*, vol. 66, pp. 82–97, 2014.
- [7] M. Manfren, P. Caputo, and G. Costa, "Paradigm shift in urban energy systems through distributed generation: Methods and models," *Appl. Energy*, vol. 88, no. 4, pp. 1032–1048, 2011.
- [8] S. Mallikarjun and H. F. Lewis, "Energy technology allocation for distributed energy resources: A strategic technology-policy framework," *Energy*, vol. 72, pp. 783–799, 2014.
- [9] N. Geron, Anne-Malorie; HONKASALO, "CHP as part of the energy transition," Belgium, 2014.
- [10] M. Geidl and G. Andersson, "Optimal Power Flow of Multiple Energy Carriers," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 145–155, Feb. 2007.
- [11] C. Stephen and M. Pierluigi, "Integrated Electrical and Gas Network Flexibility - Assessment in Low-Carbon Multi-Energy SystemsNo Title," *IEEE Trans. Sustain. Energy*, vol. 7, no. NO. 2, pp. 718–731, 2016.
- [12] L. Stougie and H. J. Van Der Kooi, "Exergy Efficient Application of LNG Cold," *Proceeding os 23rd Int. Conf. Effic. Cost. Optim. Simulation, Environ. Impact Energy Syst.*, vol. II, no. June, pp. 14–17, 2010.
- [13] D. A. Mokhtab, Saeid; Y. Mak, John;Valappil, Jaleel V.; Wood, "Chapter 4 - Energy and Exergy Analyses of Natural Gas Liquefaction Cycles," in *Handbook of Liquefied Natural Gas*, First edit., Elsevier, Ed. 2014, pp. 185–227.
- [14] T. Miyazaki, Y. . Kang, A. Akisawa, and T. Kashiwagi, "A combined power cycle using refuse incineration and LNG cold energy," *Energy*, vol. 25, no. 7, pp. 639–655, 2000.
- [15] K. Meratizaman, Mosa; Amidpour, Majid; Jazayeri, S. Ali; Naghizadeh, "Energy and exergy analyses of urban waste

- incineration cycle coupled with a cycle of changing LNG to pipeline gas," *J. Nat. Gas Sci. Eng.*, vol. 2, no. 5, pp. 217–221, 2010.
- [16] P. Mancarella, "MES (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, 2014.
- [17] M. Geidl and T. Graz, "Integrated Modeling and Optimization of Multi-Carrier Energy Systems," ETH Zurich, 2007.
- [18] X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Optimal Expansion Planning of Energy Hub With Multiple Energy Infrastructures," *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2302–2311, 2015.
- [19] A. Sheikhi, A. M. Ranjbar, F. Safe, and M. Mahmoodi, "CHP optimized selection methodology for an energy hub system," in *2011 10th International Conference on Environment and Electrical Engineering*, 2011, pp. 1–5.
- [20] K. Orehounig, R. Evins, V. Dorer, and J. Carmeliet, "Assessment of renewable energy integration for a village using the energy hub concept," *Energy Procedia*, vol. 57, pp. 940–949, 2014.
- [21] R. Evins, K. Orehounig, V. Dorer, and J. Carmeliet, "New formulations of the 'energy hub' model to address operational constraints," *Energy*, vol. 73, pp. 387–398, 2014.
- [22] M. Geidl, "Integrated Modeling and Optimization of Multi-Carrier Energy Systems," no. 17141, p. 143, 2007.
- [23] I. G. U. IGU, "Small Scale LNG, 2012-2015 Triennium Work Report," in *World Gas Conference WGC*, 2015, p. 268.
- [24] ECN; CBS, "Netherlands National Energy Outlook 2014 Netherlands National Energy Outlook 2014 Summary," no. February 2015, 2014.
- [25] A. Franco and C. Casarosa, "Thermodynamic analysis of directexpansion configurations for electricity production by LNG cold energy recovery," *Appl. Therm. Eng.*, vol. 78, pp. 649–657, 2015.