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Renewable Energy Balancing with Thermal Grid Support

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Waste heat valorisation in process industry is a common strategy today. The residual heat is converted to electricity by using steam turbines or organic Rankine cycles. As this energy conversion is likely constructed as an integral cooling capacity for the primary process, loss of electricity production will result in reduced process cooling and hence production capacity loss. This restriction prevents these generators to deliver supporting services to the electrical grid. In this paper, it is proven that coupling waste heat recovery with a district heating network provides flexibility to the electricity generation while ensuring cooling capacity to the process. This flexibility can be utilised by a Virtual Power Plant (VPP), e.g., to compensate for the variable output of renewable energy sources. Today, the power fluctuations are only compensated by traditional power plants (gas, coal) due to the scale and flexibility of these power plants. In this paper, a strategy is defined to balance variable (renewable) production with industrial waste heat. As such, some grid support tasks can be transferred from the central power plants to decentralised generation units. The backup of the variable sources is provided by utilising the local available capacity, while maintaining or improving energy efficiency of exothermal industrial processes. Operational boundaries are defined and new challenges identified. In this paper, firstly, the heat sources available for this concept are identified. Secondly, the properties of the different conversion technologies are described. Thirdly, the benefits of a virtual power plant utilising waste heat are determined. Finally, this VPP concept is verified by means of a case study in Belgium, Ostend Energy port. Available heat from biomass, chemical processing and waste incineration is used as primary energy source to balance local renewable production.

1. Introduction

In the process industry, a large amount of waste heat is available. Many industrial companies have invested in reutilising heat from one part of the process in another part. However, in many installations, there is still a large amount of residual heat. Due to the increasing carbon emission cost and rising primary energy prices, many companies prefer to utilise the waste heat for electricity production. Due to the resulting increase of overall process efficiency, the carbon footprint and the related emission cost are hence reduced.

Generation of electricity is also under pressure. As more than half of the electricity production worldwide is based on fossil fuel (IEA, 2011a), this results in environmental and economic pressure. In Europe (IEA, 2011b), the lack of large own (fossil) energy reserves enforces dependence on fuel imports. Likewise, the other prime energy resource for electricity production, nuclear power, is causing much political and social concern. These circumstances are the drivers for the development and installation of Distributed Generation (DG) like wind turbines, solar parks, Combined Heat and Power (CHP). Although these devices are mostly connected to the medium and low voltage grid, due to their large number, they have a significant impact on the high voltage grid as well. Their lack of controllability can cause significant pressure on the stability of the electric power system.

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To preserve the environment and decrease dependence of external energy sources, Europe sets ambitious goals to electricity production from renewable energy sources (RES). However, this encompasses large stress on the operational stability of the electricity grid due to a lack of controllability of these sources. Virtual Power Plants (VPPs) are a control concept to manage and control large amounts of relatively small energy resources and integrate them in the operation of the grid. In this paper, the electrical generation capacity available from waste heat valorisation is used to balance renewable sources like wind and solar power.
In §2, some of the major sources of thermal waste in the process industry are presented. In §3, different energy conversion technologies and their properties are presented. First, thermal conversion technologies available for process heat recuperation are presented, followed by renewable energy sources. In §4, the concept of a VPP is presented and it is described how this can combine the aforementioned technologies to deliver services to the electrical grid. In §5, the VPP concept is illustrated trough application in the Ostend city region in Belgium. In §6, the final conclusion is presented.

2. Available heat sources in process industry

First, an overview of some available heat sources and their properties in the process industry is given. Second, an introduction to thermal grids is presented. These grids are used as a thermal sink if the electricity demand is low to preserve energy utilisation.

2.1 Available heat sources

As mentioned in the introduction, there is an enormous amount of waste heat available in the process industry. Basically, we can consider all the streams of the process that need to be cooled as energy sources (Reverberi et al., 2011). First, as much as possible of the available heat should be recovered within the process itself. The remaining energy that cannot be used in the plant itself should be vented. Due to environmental constraints, venting to the environment is only the last possible solution. Therefore, many installations convert their residual heat to electricity.
Another very interesting use of heat is distribution into a district heating and cooling network. This is further explained in §2.2. Using waste heat provides a decrease in the use of fossil fuels (for space heating for instance) and thereby a decrease in CO_2 emissions and possibly also a cost reduction (Kapil et al., 2012). The amount of total available heat is determined as the total amount of heat available above the practical working temperature for district heating.
Waste heat is mainly coming from four types of industrial installations: chemical industry and refining, electrical power plants, CHP plants and waste incineration plants (Wetzels, 2010). CHP provides heat and electricity simultaneously. Because the production of both cannot be adjusted independently, companies using CHPs are often faced with problems of using all the produced heat when the electricity demand is high (Christidis et al., 2011) Therefore the introduction of extra heat sinks is necessary. A district heating network can therefore function as heat sink. Temporary storage of heat is an important element of these networks.

2.2 Thermal grids

District Heating (DH) and cooling networks are most spread in Northern and Eastern Europe. In Denmark for instance, district heating‘s share of the residential heating market amounted almost 50 % in 2001 (IEA, 2004). Most of this heat, ~ 80 % (Danish Energy Agency, 2008), comes from CHP-installations. In general, there are three possible energy sources for district heating, i.e. renewable energy, CHP-plants and waste heat. Rezaie and Rosen (2012) state however that government regulations –for instance taxes on CO_2-emissions- can have a significant influence on the feasibility of DH networks.
The increase in the production of energy from renewable energy sources necessitates -due to the fluctuating nature of renewable energy (Østergaard, 2012)- more flexibility in the network (Connolly et al., 2012). This flexibility can be established by the use of energy storage. According to Faninger (2004), energy storage is also required when there is a mismatch between the (thermal) energy supply and the (thermal) energy demand. This can occur for instance with the use of a CHP-installation. The storage of heat enables the system to produce heat when the electricity prices or the electricity demand is high and reduce the production when the electricity prices or demand is low. Haeseldonckx et al. (2007) show that thermal energy storage in CHP installations can improve the net reduction of CO_2 emission by factor of almost three. The main reason for is the increased continuous operation of the cogeneration unit. Nuytten et al. (2013) assessed the flexibility created by the combination of a district CHP unit and sensible heat storage. An interesting conclusion is the linear relation between the buffer size and the flexibility of the system. The power of the CHP installation on the other hand does not influence the flexibility.

Thermal energy storage, further called heat storage, currently occurs in three main physical principles for heat storage: sensible heat storage, Phase Change Materials (PCM) and chemical reactions. With sensible heat storage, the heat is retained by a material with a certain storage capacity like water, ground, rock or ceramics at a wide range of temperatures. This technology is relatively cheap but has the disadvantage of low energy density and a gliding discharging temperature. PCMs store heat in the phase change and release this heat when the material is cooled down. The energy density of these phase changing (melting or vaporisation) processes is much higher than this of sensible heat. With storage by chemical reactions, heat is added to a compound to separate it in two components. When heat is needed, the elements are brought together providing heat by the exothermal reaction.

3. Energy conversion technologies

In this section, an overview is given of different energy conversion technologies and their limitations. Four properties are analysed, as they are of crucial importance: (monthly) availability, dynamical behaviour, maximum modulation depth and maximum power.

3.1 Thermal machines

Two types of thermal cycles are discussed here. The water based steam cycle and the organic fluid based organic Rankine cycle. These are the most applied technologies to convert waste heat into electrical energy.

Steam turbines are the most used technology to produce electricity in power plants. To prevent water droplets to be formed at the exhaust of the turbine, vapour overheating is necessary. As such, the classical steam cycle requires significantly high temperatures (≥300 °C). This requirement limits the applicability of steam turbines for process heat recuperation. Also, due to lower mass flow at working points below nominal capacity, water droplets can be formed and damage the turbine. This limits the maximum modulation depth of a steam turbine.

An Organic Rankine Cycle (ORC) is technologically comparable to a steam Rankine cycle. The main difference is the use of a different working fluid. The working fluid in an ORC system has a significantly lower boiling point and is often a dry fluid, eliminating the need for overheating. These properties enable ORC systems to utilise a heat source with a much lower operating temperature. The ability of the Rankine cycle to operate at relative low temperatures (≤140°) makes this technology suitable to utilise low grade excess process heat to drive a generator and produce electrical energy.

3.2 Renewable sources

In this paragraph, some available renewable energy sources are summarised. Because in §5 the Ostend situation will be discussed, this section only discusses the available technologies in Ostend. These are mainly photovoltaic (PV), wind energy and biomass derived from municipal waste.

Photovoltaic panels

Due to the abundant governmental support (Green Certificates), a lot of PhotoVoltaic (PV) power has been installed in Flanders (Zwaenepoel et al., 2013). In the Ostend region, about 16.6 MW of PV power is available. However, typical to solar power is the relatively small size of a plant compared to traditional power plants, or even wind turbines. This can be seen in Table 1 by comparing the total power and the number of installations. In Table 1, small PV installations (≤10 kW) are excluded as investment cost for real time metering and communication cost is high compared to the total yield per installation.

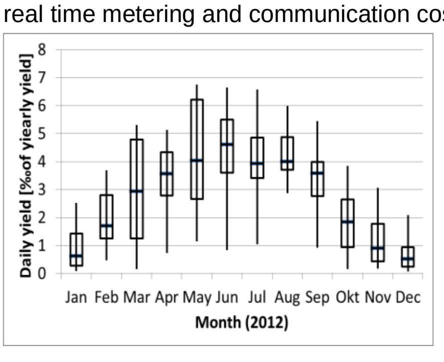

Figure 1: Relative daily PV yield in Ostend (min, Q1, median, Q3 and max)

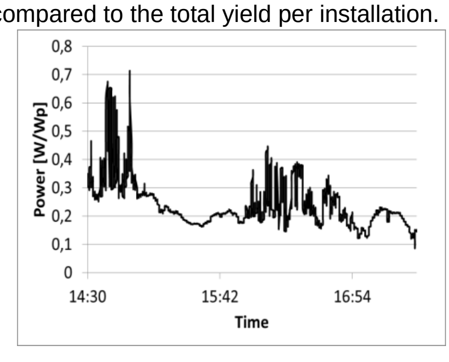

Figure 2: 10 s average of solar power (10 Oct 2011, Ostend)

In Figure 1, the relative yearly yield per month is shown. As can be expected, the average power during the summer is much higher than during the winter months. The data shown are measurements from four PV installations located in Ostend during 2012. As May was a very sunny month, the average daily yield is about as high as during July and August. However, the standard deviation is much higher, indicating much more day to day yield variation.
As PV installations are all coupled to the grid via power electronics and as there are no moving parts, the system dynamics are very high. In Figure 2, the 10 s average power of a solar installation is shown. As can be seen, halving or doubling the power within a few seconds is not uncommon.

Wind turbines

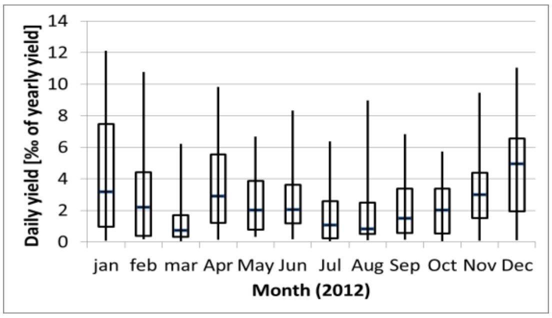

Figure 3: Relative daily wind yield (Ostend), (min, Q1, median, Q3 and max)

Wind turbines are the second RES technology available on a large scale. Although most modern wind turbines are also inverter coupled, due to the large rotational inertia of the rotor, small wind gusts are dampened out on the grid side of the inverter. This presents a more smoothed out power curve compared to PV. However, time constants are still much shorter than those of thermal units. Ping-Kwan Keung et al. (2009) describe a method to provide frequency support by discharging the kinetic energy into the grid. To prevent an equally large negative power spike to recover the kinetic energy, the recovery period of different turbines is spread over a larger time span.
Unlike for solar energy, obtaining real live power output of large wind turbines is very difficult. Therefore, in this article, the available wind power is estimated by utilising measured wind data at a height of 15 meter on the Greenbridge science park in Ostend. This wind speed is extrapolated to a height of 80 meter ($v_h = v_{15} . (h/15)^α$), as this is a typical hub height for wind turbines in the Ostend region. For α, 0.34 is chosen. With the resulting wind speed and the power curve of an Enercon E70 wind turbine (Enercon, 2010), an estimate of electrical output is calculated. Wind speeds are acquired as one minute average values. With these results, the daily energy yield is calculated and presented in Figure 3.

4. Virtual Power Plant

A VPP is a flexible representation of a portfolio of Distributed Energy Resources (DER) that can be used to make contracts in wholesale markets and to offer services to system operators (Corera and Maire, 2009).
The many small units are combined by software, hence virtual, into a controllable entity (power plant). From the grid operator's perspective, the VPP behaves as a single unit. The VPP aggregates all the information from the different small entities to provide a single 'image' of the DER state in its operating region. In the opposite direction, the VPP translates the grid operators' requests into commands for the individual participants. The VPP is an intermediate level between the grid operators and the DER units. It facilitates the interaction between all actors and enables the grid operators to have (some) control over the instantaneous DER power (El Bakari and Kling, 2010). Depending on the functionality, one can divide VPP's in two categories: Technical VPP's (TVPP) and Commercial VPPs (CVPP). A TVPP is optimised to deliver technical services to the grid. CVPPs are financial instruments to sell the energy of the DER. Ideally, a VPP is a combination of the two functionalities.
By combining the dynamic behaviour of the slow(er) thermal sources and the high dynamics of inverter coupled RES, cooperation can result in the ability to deliver fast reaction times to deliver frequency regulation services. The low internal energy storage of the RES, and hence the dependence on availability of the primary energy source, can be compensated for by the large capacity thermal sources. The primary heat source can, however, be decoupled from electricity production by shifting thermal load from the

turbine to the thermal grid. Hence, the flexibility added to waste heat recovery systems in combination with RES based electricity can be managed together in a VPP to deliver services to the grid.

5. Case study: Ostend, Belgium

In this section, this technology is applied to the Ostend region. Ostend is a sea port in Belgium with a focus on offshore energy support. In this section, the already available installations are theoretically combined to determine the possibilities of the previously described balancing technology and suggestions for expansion are made.

5.1 Renewable energy production

The available RES capacity is obtained from the Green Certificates (GC) database maintained by the Flemish energy regulator VREG. On the VREG website (VREG, 2013), a list is available of all installations receiving GC. Based on this list, the installed power of three categories of RES is determined: solar power, wind power and biomass based. This list is further narrowed down and limited to the Ostend area, as this is the area where the feasibility of a thermal grid is investigated. The available electrical power is presented in Table 1. The capacity to deliver reserve capacity to the grid is determined for two months based on measured data on the Greenbridge science park in Ostend during 2011 and 2012.

Table 1: Installed power and number of installations receiving GCs in the Ostend region

Technology	Installed Power	# of installations
Wind	15.8MW	8
Solar	16.6MW	95
Biomass	57.5MW	7

5.2 Available heat

Based on questions to large industrial companies in the Ostend outer port, it has been discovered that approximately 110 MW of residual thermal power at 140 °C is available. This power is available from four different companies. The largest thermal source is 65 MW, so about half the available power could be lost if this installation is shut down (e.g., for maintenance). Estimated total yearly thermal yield is about 890 GWh. About 55 MW of this thermal power is already converted to electricity as is mentioned in Table 1.

5.3 Energy services

The possibility to deliver frequency regulation to the transmission grid is investigated in this paragraph. The case is calculated for two different months to determine the availability. This analysis is based on measurements of wind speed and solar power on the Greenbridge science park in Ostend during June 2011 and January 2012. It should be noted that 5 min average power is used in the calculations.

Figure 4a: RES Power ≥ 10MW

Figure 4b: RES Power ≥ 10MW

As Figures 4a and 4b indicate, the time the available power from the fast RES sources is larger than 10 MW is low. 10 MW is the minimum required available power to deliver primary reserve to the transmission system operator (Elia, 2012). However, it should be further investigated if this availability should come from only the land-based RES. The wind turbines at sea could also be added in future investigations. Also part of the thermal power can be utilised to deliver (part of the) fast reacting power and increase the availability of reserve capacity. Only 40 % should be used to have permanent access to the required 10 MW controllable power (with 50 % conversion efficiency). In that case, the available RES can deliver the first reaction, only to be replaced by the thermal sources shortly later. The rest of the thermal capacity can be utilised to deliver electrical base load. The thermal flexibility needed to balance the RES based energy sources can be obtained from thermal storage in the DH grid.

5.4 Suggested expansions

As mentioned in the previous section, there is plenty of thermal capacity available to balance out current RES capacity. As a preliminary conclusion, it could be stated that there is room for more RES in the region, or the existing process industry can deliver balancing services for more RES projects outside the search area. However, not all thermal power can be utilised for balancing services, as there should be enough available to supply the customers on the thermal grid.

6. Conclusions

In this paper, the authors described how energy recovery from process industry can help to balance RES production and deliver ancillary services to the transmission grid. The combination of different dynamic behaviour and capacity can be a viable solution to mitigate RES integration problems. The combination with a thermal grid provides a flexible heat sink to guarantee sufficient process cooling while curtailing electricity production to balance RES power and meanwhile maintaining high levels of energy recuperation. However, much work is still needed to investigate the correct balance between different technologies within the VPP. This balance will depend on the available sources, the thermal demand, season, etc. Much more factors need to be taken into account to verify economic viability of this system, although this paper proved a large potential is available.

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