Combined Heat and Power

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1 INTRODUCTION

Combined heat and power (CHP) is the simultaneous production of useful heat and power in an integrated process with common fuel or energy source. Here, the basic principle and examples of processes based on using thermal energy for production of heat and power based on heat engines as well as fuel cell process are presented.

By integrating heat and power production, it is possible to use the energy source in a more efficient way and by that to reduce the environmental impact including CO₂ emissions. One of the important factors to achieve efficient utilization of fuel in an energy system is to provide a demand for both heat and power. While producing electricity, the power plant can also supply heat for the heating demand of residential buildings in colder climates and/or industrial process heat.

In 2008, the International Energy Agency (IEA) presented a report on the benefits of CHP investments and also some data on current installations. Figure 1 shows the contribution from CHP plants to the total electricity produced in the G8 and five more countries in 2005 and the potential for 2030 estimated by IEA. The total potential estimated is about twice as high in 2030 as utilized today (an increase from a share of 11% in 2005 to 24% in 2030). The report pointed out that CHP is a cost effective and important solution for reduction of CO₂ emissions. In future, the study suggested that CHP has the potential to reduce CO₂ emissions from new energy conversion installations in the world with 10% until 2030. Further, they also foresee a reduction in the investment costs, owing to lower investments in transmission and distribution

networks, which also, together with more efficient energy source utilization, can result in lower electricity prices for end consumers. (IEA, 2008).

An important trend is the development of technique and processes for small-scale and microscale CHP systems, while mature technique and processes for medium- and large-scale systems already exist. Among the mentioned reasons for developing small-scale systems are the possibility to more closely connect production and demand, better security of supply, better environmental regulation fulfillment, and more cost-efficient solutions. (Frederiksen, 2009; Liu, Shao, and Li, 2011; Moradi *et al.*, 2013; Pade *et al.*, 2013).

Important research questions related to CHP are how to optimize the operation of CHP plants from an economic and environmental point of view. The development of new CHP energy systems is also conducted with multiple products, the so-called polygeneration with careful considerations of load demands. How to integrate renewable energy resources into the CHP plants is another important topic of interest.

2 BASIC PRINCIPLES OF THERMODYNAMIC CYCLES OF CHP

The thermal energy processes used for CHP can be related to three types of processes, the Rankine or steam cycle, the Brayton or Joule cycle, and internal combustion engines. In the Rankine cycle, a circulating working fluid, usually water, passes through a four-step process. The steps for an ideal process are reversible, adiabatic compression; heat uptake at constant pressure (formation of steam); reversible, adiabatic expansion, and heat release at constant pressure. Power is produced in the expansion step and heat is produced in the heat release step. The Brayton cycle can be described with the same process steps as the Rankine cycle but with

Figure 1. The share of the electricity production in the G8 plus five countries produced in CHP plants in 2005 and the potential estimated for 2030. *Source:* Based on graphs reported in IEA, 2008.

the difference that the working fluid is a gas in all process steps. The Brayton cycle is often run as an open cycle without circulation of the working fluid. In this case air is compressed, a fuel is combusted in the compressed air, the flue gases are expanded and heat released by heat exchange before the flue gases are released to the surrounding air. In the internal combustion engine the working fluid is also a gas. However, in this process, all process steps take place in one process component—the engine cylinder. Two different cycle processes are common—the Otto cycle and the Diesel cycle. The ideal Otto cycle consists of reversible, adiabatic compression; heat uptake at constant volume; reversible, adiabatic expansion, and heat release at constant volume. In the ideal Diesel cycle, the heat uptake takes place at constant pressure instead of at constant volume. The Stirling engine is also of interest for CHP. Instead of heating the working fluid with internal combustion of a fuel this engine uses an external heat source but otherwise following the process steps of the ideal Otto cycle.

The fuel cell process is based on electrochemical energy conversion. The power from the process is produced by the electrons released in the electrochemical reactions and the heat produced comes from recovery of heat due to losses in the electrochemical process. This is then a major difference from the thermal-based processes where the heat release is a necessity for the power production.

The efficiency of a power cycle is usually described with the efficiency defined as the ratio of useful energy output and energy input. The thermal efficiency, also called power efficiency, for a power plant is defined as the ratio of the output of power (or work) and the heat input. For a CHP plant the useful energy output is both the power and the heat. It is therefore relevant to also use a total efficiency—the ratio

of the sum of output of power and heat and the heat input. The energy content of a fuel is usually described by its lower heating value (LHV), considering the water formed to be in the gaseous phase. In CHP plants, it is possible to increase the heat utilization by flue gas condensation. This results in that the total plant efficiency might reach more than 100% if the energy content of the fuel still is represented by the LHV.

The size of a CHP plant can range from several hundreds of megawatts of fuel input to plants delivering heat for a district heating network of a whole city down to micro-CHP plants with energy inputs down to kilowatt level supplying a one-family house.

3 CHP SYSTEMS

The CHP system consists of the energy source, the energy conversion process, and demand side with the use of the produced heat and electricity. CHP plants can utilize many different types of energy sources. Fossil fuel and biomass-based energy sources can be used in all the above-mentioned types of processes. Nuclear power can also be used as a fuel for Rankine cycle-based processes even though it is not common for CHP applications. Waste heat from other processes can be utilized as the energy source in the thermal-based processes and also geothermal and solar heat can be used. The fuel cell process is also combined with hydrogen production from wind or solar power. Principally, that would be possible also for the thermal conversion processes. A large part of the solid biomass utilized for heat production in Europe is used in CHP plants (about 60% in 2011). Also a substantial part of the biogas (40% in 2011) used for power and heat production in Europe are used in CHP plants. (Euroserver, 2012a,b).

The heat produced can be used for different heat demands, for example, a district heating network, an individual building, or industrial processes. Different types of conversion processes are possible for different applications and systems based on different conversion techniques are described in the following sections.

3.1 Steam turbine-based CHP

In a steam turbine plant for power production, the conditions for the heat release after expansion is designed for maximum power output, which means using as cold cooling water as possible giving a low pressure after the turbine. For a CHP plant the heat demand needs to be met and the pressure in the condenser is determined by the supply temperature for the district heating network. The balance between the output of power and the heat supply is an important parameter for the performance of the plant. This is described by the ratio between the electric power and the heat power (α -value). A lower heat supply temperature increases the power efficiency of the plant. When the heat sink is a district heating network the heat comfort of the customers is in focus. The heat demand of the customers is known to be depending mostly on outdoor temperature and human behavior (Gustafsson, Delsing, and Deventer, 2011; Dotzauer, 2002). To optimize the CHP plant performance, the heating load changes and variation with time of the district heating network are important (Starfelt *et al.*, 2012a).

The principle of a (simple) steam turbine-based CHP plant is shown in Figure 2. In a CHP plant, the power production is completely dependent on the heat demand. If the heat demand is low the power production will also be low. There are some ways to increase the power production above what

is given by the heat demand (will be described later). The total efficiency of CHP plants will be around 90%. The losses are heat losses from the boiler and mechanical/electrical losses from the turbine/generator. The total efficiency is therefore not sufficient to describe the system performance of the CHP plant. Another performance indicator, called the α -value, is introduced in a CHP plant. For the same heat demand, a plant with a better (more advanced) turbine process will produce more electricity and have a higher α -value.

If a change of a certain parameter gives a higher thermal efficiency for a condensing power station, the same change will give a higher α -value for a CHP plant. A very simple plant with a steam pressure of 40 bar and a temperature of 450°C at the turbine inlet will give an α -value of about 0.33 if the supply temperature to the district heating system is 80°C. An advanced CHP plant with 180 bar and 540/540°C (superheat/reheat), five stages of feed water heating and two condensers in series (65 and 80°C forward temperatures) will give an α -value of about 0.66. It means that the advanced plant produces twice as much electrical power compared to the simple plant for the same heat demand. The higher the price of electricity the more advanced plant may be used. A comparison of different alternatives is shown in Figure 3. The heat production is the same in all four cases in the figure (100 units), and Figure 3a and 3c refers to the two cases with α -value of 0.33 and 0.66, respectively.

There are several opportunities to design a CHP steam plant to increase the power efficiency and the security of heat supply. Heat supply without running the steam turbine is possible when connecting the high pressure and low pressure sides with an expansion valve. The boiler and turbine can also be divided into several parts making it possible to run

Figure 2. The principle of a simple steam turbine-based CHP plant.

Figure 3. The differences in conversion efficiency of CHP production compared to separate production of electricity and heat with (a) a simple steam turbine-based combined power and heat plant, (b) separate production of electricity and heat (compared to simple combined power and heat production), (c) an advanced steam turbine-based combined power and heat plant, and (d) separate production of electricity and heat (compared to advanced combined power and heat production). The heat production is the same in all cases (100 units). Figure (a) and (c) shows the possible production of electricity in the combined cases producing 100 units of heat and the amount of fuel needed while (b) and (d) shows the corresponding need for fuel to produce the same amount of units of both electricity and heat in separate production plants.

part of the plant if another part fails. It is also possible to design the plant for higher power production than the heat demand admits. An additional turbine connected to a low temperature heat sink, without heat recovery, can be added. Other possibilities are to increase the steam flow in the CHP turbine by connection of a steam or hot water accumulator or the possibility to release part of the steam to the atmosphere (Wester, 2009).

Reheating is commonly used in steam turbine power plants to increase the power efficiency. However, with a high condensing pressure, as in CHP plants, the benefit is smaller and only economical for larger plants (Wester, 2009).

It is also possible to use other working fluids instead of water in a Rankine cycle-based CHP plant. The organic Rankine cycle (ORC) uses an organic substance as working fluid that makes it possible to use low temperature sources, for example, waste heat, geothermal heat, and solar heat, as the energy source. An example of a CHP concept utilizing the ORC technique is small-scale (0.4–1.2 MW produced electric power) plants with a biomass burned boiler heating

thermal oil that is used as the heat source for the ORC. Heat is produced both in the ORC condenser and with the flue gases from the boiler. There are also concepts using hot water instead of thermal oil. The ORC cycle can be operated at a lower pressure than a cycle with water as working fluid. These systems are mature and are commercially available. There are also examples of ORC-based CHP systems using solar heat as the energy source (Fredriksen, 2009; Liu, Shao, and Li, 2011; Tchanche *et al.*, 2011).

The Kalina cycle, using a mixture of ammonia and water as working fluid, has also been investigated for CHP applications (Dejfors, Thorin, and Svedberg, 1998).

3.2 Gas turbine-based CHP

The gas turbine cycle is one possible process for the so-called micro-CHP systems where power and heat are produced for small demands, for example, for one building or household, also called distributed generation.

Figure 4. PowerSeraya's completed cogeneration project at Jurong Island in Singapore. *Source:* Reproduced with permission. © Siemens AG.

Larger gas turbines can also be used combined with a steam turbine where the exhaust gases from the gas turbine produce superheated steam. This system is called *combined cycle* and in Figure 4 an existing combined cycle is shown. The steam is used in a CHP plant similar to those described earlier. The steam cycle is in this case called *bottoming cycle* as it uses heat from another power cycle, the gas turbine cycle, as energy source. In this case very high α -values (around 1.0) can be reached. If there is only demand for electricity and no heat demand for the CHP system, the gas turbine may be operated without the steam turbine that can produce about 2/3 of the output of electrical power. However, in the CHP with combined cycle, the steam turbine cannot be operated without heat demand.

Several advanced gas turbine CHP configurations are possible and have been studied, including evaporative gas turbine CHP plants (Yan, Eidensten, and Svedberg, 1994; Eidensten, Yan, and Svedberg, 1996; Jonsson and Yan, 2005). Gas turbine cogeneration can also be applied in different applications (Starfelt and Yan, 2008).

3.3 Engine-based CHP

For engines, heat can be extracted from the cooling system and also from the hot flue gases. Gas engines are common in CHP plants in the small-scale range (<10 MW electric power production). In this range, it shows higher power efficiencies than steam turbine-based CHP plants (α -value around 1.0). Engine-based systems are common for CHP based on biogas from anaerobic digestion. Gas from thermal gasification is another possible fuel. In Güssing, Austria, a CHP pilot plant with gasification of biomass and gas engine is run. (Frederiksen, 2009).

Figure 5. An example of an engine-based CHP system for small commercial buildings. *Source:* Reproduced with permission from Mago, Chamra, and Hueffed, 2009. © John Wiley & Sons, Ltd.

Figure 5 shows an example of an engine-based CHP system for small commercial buildings. Here the engine is run to fulfill the electricity demand of the building including lighting, appliances, and equipment as well as cooling of the building with a vapor compression system. The waste heat of the engine is used for the heating and hot water demand of the building. In this case the system is designed to follow the electricity demand of the building and a boiler is needed to fulfill the heat demand. It would also be possible to design

the system based on the heat load but then the surplus of electricity produced needs to be possible to deliver to the electricity grid (Mago, Chamra, and Hueffed, 2009).

It is also possible to combine engines with bottoming cycles. One example is to use the Kalina cycle as a bottoming cycle. It has been shown that the potential for improving energy efficiency of engine-based systems through combined cycle can be significant (Jonsson, Thorin, and Svedberg, 1999; Jonsson and Yan, 2000a, 2000b, 2000c, 2001).

3.4 Fuel-cell based CHP

There are several different types of fuel cells with different electrolytes and different electrode reactions. The proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), and phosphoric acid fuel cells (PAFC) have all been used for CHP applications. SOFC and MCFC are operated at high temperatures (800–1000°C and 600–700°C, respectively) and can also be used in combined cycles including a bottoming cycle. However, CHP based on fuel cells are mostly of interest for distributed generation and small-scale systems. Another advantage of the high temperature fuel cell, also important for small-scale systems, is the possibility for internal reforming of fuels making a fuel cell-based CHP system fuel flexible.

Micro-CHP based on fuel cells has been suggested to be a way to manage fluctuations in renewable energy supply by wind and solar power. However, to realize this solution the costs of the fuel cell technique needs to be reduced (Pade *et al.*, 2013; De Paepe, D’Herdt, and Mertens, 2006).

Pruitt, Bran, and Newman (2013), investigated the economic viability of an SOFC CHP system in a building, using natural gas as the fuel. They conclude that the costs need to be reduced to one-fifths of the current cost to make it economically viable. However, variability in utility energy pricing and different policy measures make the picture complex. They also point out the importance of balance between energy savings and carbon dioxide emissions, using fossil fuels.

On the homepage Fuel cells 2000 [www.fuelcells.org, managed by Breakthrough Technologies Institute (BTI), an independent, nonprofit, educational organization] a database with fuel cell installations all over the world, USA excluded, can be found. From 1990 to 2013, 611 installations for stationary fuel cells are presented. Of those almost one-third of the systems are CHP installations.

3.5 Polygeneration

In CHP plants using a district heating network as heat sink, the operating load is determined by the heat demand

in the network. As the heat demand usually varies during the year the full-load operating time of the production unit can be limited. An example is a steam turbine-based CHP plant for a Swedish small town where the full-load operating time is as low as 10–20% of the year (Starfelt *et al.*, 2012a, Starfelt *et al.*, 2012b). By introducing other heat demanding processes as, for example, ethanol production and pellet production, in biomass-based CHP plants, the full-load operating time can be increased. The yearly production of electricity from biomass is then also increased. When evaluating the economic and environmental benefit of the polygeneration plant it is important to include the whole system, both the CHP plant and the heat demanding process. Optimal operation conditions can be different in polygeneration plants compared to separated processes. Integration of several processes can also give environmental benefits such as lower CO₂ emissions compared to separated processes. Integrating ethanol production from straw in a CHP plant can be an efficient way to increase the utilization of straw for CHP production as the ethanol production residues has been found to be a higher quality fuel and easier to combust than the straw itself. The CHP can also be further improved by introducing biomass pellets production to improve the performance of operation in particular when heat demand is low. (Starfelt *et al.*, 2010; Starfelt *et al.*, 2012a, Starfelt *et al.*, 2012b; Song *et al.*, 2011; Wahlund, Yan, and Westermarck, 2002).

4 APPLICATIONS

Sweden is an example of a country with cold climate where CHP production is widely used for covering part of the heat demand in buildings by district heating. Most plants are steam turbine based with biomass as fuel feedstock. Table 1 describes examples of existing CHP plants in Sweden and their characteristics. Examples of plants in other parts of the world are provided in Table 2. The examples also include other conversion processes than the steam turbine based and illustrate the range of sizes and variety of energy sources used.

The profitability of CHP plants depends not only on many different parameters such as energy prices, technology used, location and size but also on operational strategy. The operational strategy can, for example, be to run the plant continuously, to follow the electricity demand, to follow the heat demand, and/or to include a heat storage option (Fragaki, Andersen, and Toke, 2008; Ghadimi, Kara, and Kornfeld, 2014; Taljan *et al.*, 2012). Westner and Madlener (2011) compared different CHP technologies from a return and risk perspective using mean-variance portfolio theory for the

Table 1. Some examples of steam turbine-based CHP plants in Sweden.

Plant (year built)	Energy Source	Capacity	Steam Data	Efficiency (%)	Comment
Borås Energi och miljö (2004)	Household and industrial waste 100,000 ton/yr	40 MW _{th} * 10 MW _{el}	49/405 [bar/°C]	89	
Renova, Gothenburg (1994, 1995, 2001)	Household and industrial waste 500,000 ton/yr	157 MW _{th}	40/400 [bar/°C]	89	Flue gas condensing
Mälarenergi, Västerås (2000)	Biomass, peat	600 MW _{th} 330 MW _{el}	171/540/540 [bar/°C/°C]	90	Reheat, flue gas condensing
Eskilstuna Energi och Miljö	Wood	122 MW _{th} 39 MW _{el} 70 MW _{heat}	140/500 [bar/°C]	89	25 MW _{heat} from flue gas condensing
Gällivare Energi (2010/2011)	Peat	34 MW _{th} 8 MW _{el} 20 MW _{heat}	81/485 [bar/°C]	85	5 MW _{heat} from flue gas condensing
Lugnvikverket, Östersund	Wood	134 MW _{th} 45 MW _{el} 80 MW _{heat}	145/540 [bar/°C]	92	27 MW _{heat} from flue gas condensing
Lycksele (2000)	Wood and peat	51 MW _{th} 16 MW _{el} 31 MW _{heat}	88/520 [bar/°C]	91	
Sala Heby Energi	Wood	36 MW _{th} 10 MW _{el} 22 MW _{heat}	80/480 [bar/°C]	88	9 MW _{heat} from flue gas condensing
Hedensbyn, Skellefteå (1996)	Wood	99 MW _{th} 33 MW _{el} 57 MW _{heat}	140/540 [bar/°C]	91	

*th, thermal energy from combustion.

Source: Created using data from Johansson *et al.*, 2009; Mälarenergi, 2014; Wester, personal communication; Gällivare Energi, 2014; Skellefteå Kraft, 2014.

German market. The technologies compared were large coal-fired CHP plants, combined-cycle gas turbine-based CHP (CCGT-CHP), engine-based CHP, and microturbine CHP. Their results show that combined-cycle gas turbine-based CHP and engine-based CHP give the best return, whereas the microturbine CHP shows the lowest risk exposure.

5 IMPLEMENTATION AND POLICY INCENTIVES

Several barriers, related both to the market and regulations, exist for implementation of CHP, for example, lack of knowledge about the benefits of CHP, lack of integrated planning, lack of common methods to identify and quantify energy savings and environmental benefits and difficulties related to access to the electrical grid. Therefore policies are necessary to be able to develop the potential of CHP in the world (IEA, 2008).

The European Parliament and the Council of the European Union, decided on a directive (Directive 2004/8/EC) for

promotion of cogeneration of heat and power in 2004 with the aim to save energy and reduce greenhouse gas emissions. The tasks for the member states in the directive include analysis of the potential as well as ensuring support for CHP production and reporting the progress. Owing to the colder climate in the northern part of Europe, the member states in those parts have greater potentials for CHP production compared to the member states in the southern part. Figure 6 shows the reported progress for some of the membership countries. All countries do not report with the same detail. Besides the value reported for the share of the total electricity production provided by CHP in 2009, the German report also states an increase of 1.5% from 2002 (EU, 2013).

EPA, US Environmental Protection Agency, initiated a voluntary program called *CHP partnership* with the aim to promote the use of CHP in the United States. The program started in 2001 and supported development and investigations of CHP by providing the partners in the program with information, tools, and platforms for establishing relationships (EPA, 2013). In the United States, several states have incentives for CHP in their climate policy plans.

Table 2. Examples of existing CHP plants in the world.

Plant (year built)	Energy Source	Capacity	Conversion Process	Technical Data	Efficiency (%)	Comment
Apar Industries, Ankleshwar, India (2000)	Natural gas	1.5 MW _{el}	Gas turbine	Inlet air cooling (15°C)	64	4 017 ton CO ₂ /yr avoided compared to separate production
Shanghai Pudong International Airport, China	Natural gas	4.6 MW _{el}	Gas turbine	Heat recovery steam generator 8/185 [bar/°C]	74	
Vattenfall, Fynsverket, Denmark (2009)	Straw 150,000 ton/yr	35 MW _{el} 75 MW _{heat}	Steam turbine	Steam data 110/540 [bar/°C]	El. 33	11 MW _{heat} from flue gas condensing
Great River Energy, Spiritwood, North Dakota, USA (2012)	Lignite coal	275 MW _{th} 90 MW _{el}	Steam turbine	Steam data 125/541 [bar/°C]		Delivery of steam to malt plant
Sharp Electronics Kameyama manufacturing facility, Japan (2006)	Natural gas	1 MW _{el}	Molten carbonate fuel cell			Calculated to reduce CO ₂ emissions with 2300 tons
EWE, Oldenburg, Germany (2008)	NA	1 kW _{el}	Solid oxide fuel cell			Residential plant
Cool Endeavour, Amsterdam, Netherlands (2011)	NA	2 kW _{el}	Solid oxide fuel cell			Building, proof of concept project
NegH Biostrom KEG, Paldau, Austria (2001)	Biogas	2 × 250 kW _{el} available heat 7250 MWh/yr	Gas engine		El. 37%	17% of available heat used owing to lack of heat demand

Source: Created using data from IEA, 2008; Hinge, 2009; Babcock and Wilcox Power Generation Group, 2011; Sharp Electronics Corporation, 2013; Breakthrough Technology Institute, 2013; Amsterdam Smart City, 2014; Woess-Gallasch *et al.*, 2011.

IEA, International Energy Agency, has analyzed different policies applied in the world for promotion of CHP and reported examples of different approaches with good results. IEA divides the possible measures into six different categories “financial and fiscal support, utility supply obligations, local infrastructure and heat planning, climate change mitigation, interconnection measures and capacity building” (IEA, International Energy Agency, 2008; IEA, 2009).

To improve the competitiveness of CHP plants in liberalized electricity market, tools for optimization of the unit commitment and dispatch can be used. Both fulfillment of the heat demand and the possibility for trading electricity are then considered when planning the operation of the plant. Also the provision of secondary reserve can be considered. The development of optimization tools includes several different approaches, for example, linear programming, nonlinear programming, fuzzy programming, Lagrangian relaxation, and genetic algorithms (Thorin, Brand, and

Weber, 2005; Pirouti *et al.*, 2011; Dvorák and Havel, 2013; Moradi *et al.*, 2013).

6 CONCLUSION

CHP is a cost effective and important solution for reduction of CO₂ emissions and the potential for electricity production in CHP plants in the G8 and plus five countries (Brazil, China, India, Mexico, South Africa) has been estimated to be about twice as high as utilized today.

CHP plants can utilize many different energy sources such as fossil fuels, biomass, nuclear power, waste heat, geothermal energy, and solar energy. A large part of the solid biomass and biogas utilized for energy purposes in Europe are used in CHP plants.

The size of a CHP plant can range from several hundreds of megawatts of fuel input to plants delivering heat for a district heating net of a whole city down to micro-CHP plants with energy inputs down to kilowatt level supplying

Figure 6. The development of the share of (a) electricity and (b) heat production provided by CHP in some EU membership countries. Source: Reproduced from EU, 2013.

a one-family house. The most commonly used technique, for large-scale CHP plants, is the steam turbine process or the combined gas turbine and steam turbine process. Gas turbines, engines, and fuel cell processes are usually used for small-scale plants (<10 MW electric power production).

The α -value, the ratio between the output of power and the heat supply, is an important parameter for the performance of a combined power and heat plant. The higher the price of electricity the more advanced plant, with a higher α -value, may be used.

Incentives for promotion of combined power and heat production can be found in the world, for example, in Europe and the United States. Many approaches can also be found in the development of optimization tools for improving the competitiveness of CHP plants in liberalized electric power markets. Both fulfillment of the heat demand, the possibility for trading electric power, and the provision of secondary reserve are important to consider.

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