
Short title: Integrating Renewable Energy & Waste Heat

Date of Publication: 2014-09-10

Authors:
Mark Spurr
Todd Sivertsson
Eric Moe
Marti Lehtmets
This page is empty on purpose.

Contents

Contents.................................................................................................................................................. 3
Figures.................................................................................................................................................. 8
Tables .................................................................................................................................................. 11
Executive Summary ............................................................................................................................ 12

1 General Preface Annex X 2011 - 2014.......................................................................................... 24
  1.1 Introduction ................................................................................................................................... 24
  1.2 The Major International R&D Programme for DHC/CHP.......................................................... 24
  1.3 Annex X....................................................................................................................................... 25
  1.4 Benefits of Membership................................................................................................................. 26
  1.5 Information .................................................................................................................................. 26

2 Introduction ....................................................................................................................................... 27
  2.1 Purpose......................................................................................................................................... 27
  2.2 Acknowledgments ......................................................................................................................... 27
  2.3 Report Structure ............................................................................................................................ 28

3 Case Studies....................................................................................................................................... 29
  3.1 Individual Case Studies ................................................................................................................. 29
  3.2 Country Transitions to REWH........................................................................................................ 30
    3.2.1 Sweden.................................................................................................................................. 30
    3.2.2 Denmark................................................................................................................................. 31

4 Renewable and Waste Heat Resources............................................................................................ 32
  4.1 Introduction .................................................................................................................................... 32
  4.2 Combined Heat and Power (CHP).................................................................................................. 32
  4.3 Bioenergy....................................................................................................................................... 33
    4.3.1 Introduction............................................................................................................................. 33
    4.3.2 Biomass................................................................................................................................... 33
    4.3.3 Bioliquids............................................................................................................................... 38
4.3.4 Biogas

4.3.5 Summary Comparison of Biomass Direct Combustion and Gasification

4.4 Municipal Solid Waste

4.4.1 Waste to Energy Technologies

4.4.2 Implementation of WTE

4.5 Geothermal Heating

4.6 Solar Thermal

4.6.1 Flat Plate Solar Collectors

4.6.2 Evacuated Tube Solar Collectors

4.6.3 Concentrating Solar Collectors

4.7 Wind

4.8 Deep Water Cooling

4.8.1 Technology Configurations

4.8.2 Implementation

4.8.3 Efficiency

4.8.4 Economic Factors

4.8.5 Reliability

4.9 Heat Pump Technologies

4.9.1 Geo-Exchange

4.9.2 Chiller Heat Recovery

4.9.3 Sewage Heat Recovery

4.10 Industrial Waste Heat Recovery

4.11 Flue Gas Heat Recovery

5 Fundamental Considerations for Integrating REWH

5.1 Introduction

5.2 Technical Considerations

5.2.1 Impact of Temperature
5.2.2 Impact of Load Availability ................................................................. 74

5.3 Business Considerations ........................................................................ 76
  5.3.1 Fundamental Drivers ........................................................................... 76
  5.3.2 Production Considerations ................................................................. 77
  5.3.3 Customer Considerations .................................................................... 77
  5.3.4 Policy Issues ....................................................................................... 78

6 Optimization Analysis for Integrating REWH ............................................. 79
  6.1 Framework for Considering REWH Resources ...................................... 79
  6.2 Temperature Characteristic Evaluation ............................................... 79
    6.2.1 Building System Temperatures vs. DES Temperatures .................... 79
    6.2.2 Mitigating Issues Related to Reduced District Heating Temperatures .... 81
    6.2.3 DES Temperatures vs. REWH Temperatures .................................... 81
  6.3 Availability Characteristic Evaluation ................................................. 83
    6.3.1 Dispatchable ..................................................................................... 83
    6.3.2 Correlated with DES Load ............................................................... 83
    6.3.3 Site Specific Annual Pattern ............................................................. 84
    6.3.4 Intermittent ...................................................................................... 84
    6.3.5 Assessing Short-Term Thermal Storage ........................................... 85
    6.3.6 Assessing Seasonal Storage ............................................................ 87

7 Recommendations ....................................................................................... 89
  7.1 General Recommendations ..................................................................... 89
    7.1.1 Confirmation of Goals ....................................................................... 89
    7.1.2 DES Loads and Temperatures .......................................................... 89
    7.1.3 Resource Assessment ....................................................................... 90
    7.1.4 Integrated Assessment ..................................................................... 90
    7.1.5 Monitoring and Controls ................................................................. 91
    7.1.6 Resource Contracts ......................................................................... 92

7.1.7 Customer Contracts ................................................................. 92
7.1.8 Life Cycle Economic Analysis .................................................. 92
7.2 Resource-Specific Recommendations ......................................... 93
  7.2.1 Bioenergy ............................................................................. 94
  7.2.2 Municipal Solid Waste .......................................................... 95
  7.2.3 Geothermal Heating .............................................................. 95
  7.2.4 Solar Thermal ................................................................. 96
  7.2.5 Wind ................................................................................. 97
  7.2.6 Deep Water Cooling ............................................................. 98
  7.2.7 Heat Pump Technologies ...................................................... 98
  7.2.8 Industrial Waste Heat Recovery ........................................... 100
  7.2.9 Flue Gas Heat Recovery (FGHR) ......................................... 101

8 Abbreviations and Key Definitions ................................................. 102
  8.1 Abbreviations ....................................................................... 102
  8.2 Key Definitions ..................................................................... 104

9 Appendices – Case Studies ........................................................... 105
  9.1 Ball State University ............................................................... 106
  9.2 Jena ....................................................................................... 110
  9.3 Greater Copenhagen Area District Heating ............................... 113
  9.4 Toronto Deep Lake Water Cooling ......................................... 118
  9.5 Stockholm District Cooling ..................................................... 121
  9.6 Solar Village Wiggenhausen-South .......................................... 125
  9.7 Húsavik Geothermal Power Plant .......................................... 129
  9.8 Munkegårde District Heating Plant .......................................... 132
  9.9 Lindesberg District System ..................................................... 134
  9.10 Norrköping Multiple Energy Source System .......................... 136
  9.11 Östergötland Municipal Waste Management .......................... 138
9.12  Princeton University .......................................................... 142
9.13  Skagen District Heating System ........................................... 147
9.14  Southampton District Energy Scheme .................................. 150
9.15  Stanford University Chiller Heat Recovery .......................... 153
9.16  Turku Energy District System ............................................. 158
9.17  Vancouver Sewer Heat Recovery ........................................ 161
9.18  District Energy St. Paul (Overview) ..................................... 164
9.19  St. Paul Solar Thermal Project (Detailed Case Study) ............ 168
Figures

Figure 1. Relevance of Case Studies for each REWH Resource or Storage Technology .......... 29
Figure 2. Transition of Swedish District Heating Fuels from Oil to Renewable Energy, 1980- 2008 ................................................................................................................................. 30
Figure 3. Transition of Danish District Heating Fuels, 1980-2010 ........................................ 31
Figure 4. Impact of Temperature on Extraction COP in Steam Cycle CHP (Turbine Efficiency 0.85) .................................................................................................................................. 33
Figure 5. Debarked and Screened Chips ........................................................................... 34
Figure 6. Bark .................................................................................................................. 35
Figure 7. Sawdust .......................................................................................................... 35
Figure 8. Wood Pellets .................................................................................................. 36
Figure 9. Torrefied Wood Pellets .................................................................................... 36
Figure 10. Organic Rankine Cycle Process Overview ......................................................... 38
Figure 11. Biomass Gasification Facility at Oak Ridge National Laboratory ..................... 40
Figure 12. Anaerobic Digestion Process Overview .............................................................. 41
Figure 13. Biogas Refueling Station, Linkoping, Sweden .................................................. 42
Figure 14. Energy from waste facility, Coventry UK ............................................................ 45
Figure 15. Geothermal Reservoir and Temperatures in the Earth ........................................ 46
Figure 16. Flat Plate Solar Thermal Collectors .................................................................. 47
Figure 17. Efficiency of Flat Plate Solar Collectors .............................................................. 47
Figure 18. Evacuated Tube Solar Collector ....................................................................... 48
Figure 19. Efficiency Comparison between Evacuated Tube and Flat Plate Solar Collectors . 49
Figure 20. Parabolic Trough Concentrating Solar Collector ................................................ 50
Figure 21. Pipe Installation in Lake Mälaren, Sweden ......................................................... 52
Figure 22. Heat Pump COP vs. Temperature Lift ................................................................ 54
Figure 23. Vertical Borehole Geoxchange System .............................................................. 56
Figure 24. Actual Ground Source Heat Pump Heating Efficiencies Based on Field Measurements in the United Kingdom ........................................................................ 57
Figure 25. Illustrative Daily Heating and Cooling Load Profile ........................................... 58
Figure 26. Chiller Heat Pump Temperature Scheme, Stanford University .......................... 59
Figure 27. False Creek Energy Centre, Illustrative Schematic ........................................ 60
Figure 28. Efficiency Improvement from Flue Gas Condensation (Example) ...................... 61
Figure 29. Condensing Flue Gas Heat Recovery Unit ....................................................... 62
Figure 30. Representative Temperatures of Selected REWH Resources ............................ 64
Figure 31. Representative District Heating Temperature Regimes (Peak Conditions) ......... 65
Figure 32. Examples of Hot Water Temperature Schemes as a Function of Outdoor Air Temperature ........................................................................................................ 68
Figure 33. Example of Hot Water Temperature Schemes as a Function of Hours ............... 69
Figure 34. Annual Average Supply and Return Temperatures for 140 Swedish District Heating Systems ........................................................................................................ 70
Figure 35. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of High Pressure Steam ........................................ 71
Figure 36. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of Low Pressure Steam ........................................ 72
Figure 37. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of High Temperature Hot Water ........................ 72
Figure 38. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of Medium Temperature Hot Water ................. 73
Figure 39. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of Low Temperature Hot Water ......................... 73
Figure 40. Example of Load Duration Curve (LDC) for a DES ........................................ 74
Figure 41. Example of LDC with Seasonal Storage ............................................................. 76
Figure 42. Example of Combined LDC for Heating and Cooling Loads ............................. 84
Figure 43. Hot Water Accumulator .................................................................................... 86
Figure 44. ATES at Arlanda Airport, Winter (left) and Summer (right) Operation ............... 87
Figure 45. District Energy St. Paul Service Area Map ......................................................... 170
Figure 46. RiverCentre Pre-Installation Aerial View ......................................................... 171
Figure 47. Steel Exoskeleton ............................................................................................. 171
Figure 48. Steel Bracing

Figure 49. Collector Efficiency Data for Competitive Bidders (at varying degrees C difference between collector temperature and ambient)

Figure 50. Arcon HT-SA 28/10

Figure 51. Installation of Collector

Figure 52. North Roof Collectors

Figure 53. Aerial View of Solar Installation

Figure 54. Components of Installation

Figure 55. Manifold Pipe

Figure 56. Manifold System

Figure 57. Mechanical Area

Figure 58. Schematic Overview

Figure 59. Pumps

Figure 60. District Energy System

Figure 61. Containment and Expansion Tanks

Figure 62. Control Collector and Meters

Figure 63. PHX Controls Screen

Figure 64. AHX Controls Screen

Figure 65. DHX Controls Screen

Figure 66. Solar Output: Actual & Estimated

Figure 67. Monthly Energy Conventional and Solar (2011)

Tables

Table 1. Comparative Strengths and Weaknesses of Biomass Direct Combustion and Gasification ........................................................................................................................................... 42

Table 2. Representative Supply and Return Temperatures (Peak Condition) for Five Types of District Heating Systems ........................................................................................................................................... 66

Table 3. Representative Peak, Setback and Annual Average Temperatures for High, Medium and Low Regimes ........................................................................................................................................... 69

Table 4. Resource Categories ........................................................................................................................................................................................................... 79

Table 5. Overview of Key Resource-Specific Issues ........................................................................................................................................................................................................... 94

Table 6. St. Paul Solar Installation General Information ........................................................................................................................................................................................................... 168

Table 7. Solar System Specifications ........................................................................................................................................................................................................... 179

Table 8. Heat Exchangers ........................................................................................................................................................................................................... 183

Table 9. Pumps ........................................................................................................................................................................................................... 185

Table 10. St. Paul Solar Installation General Information ........................................................................................................................................................................................................... 186

Table 11. District Heating System Specifications ........................................................................................................................................................................................................... 188

Table 12. Monthly Energy Data ........................................................................................................................................................................................................... 195
Executive Summary

A key argument in favor of district energy from a policy perspective is its ability to facilitate use of renewable thermal energy and waste heat resources (REWH). These low- or no-carbon energy sources include bioenergy, combined heat and power (CHP), industrial waste heat, municipal solid waste combustion, landfill gas, solar thermal, geothermal hot water and deep water cooling. District energy systems can facilitate optimized use of heat pumps to convert extremely low-temperature resources such as groundwater and sewage effluent into useful thermal energy because in a district energy system heat pumps can be integrated with other sources to provide more efficient and reliable thermal service.

Combined heat and power (CHP) is not a resource but rather a range of conversion technologies which convert renewable or non-renewable resources into power and heat. For this reason, and given that the unique issues which arise with integration of CHP have been addressed in other reports, this report addresses CHP only briefly.

This project is intended to guide evaluation of options for integrating renewables and waste heat with existing or potential district energy systems (DES), addressing economic, design and operational issues, including fundamental issues relating to operating temperatures and availability. Case studies were developed to: illustrate a range of examples of integration of REWH in DES; illuminate key design issues associated with such integration; and describe solutions to addressing these issues.

Fundamental Considerations

There are two fundamental technical characteristics which must be addressed when evaluating integration of REWH into a DES:

- **Temperature** – at what temperature is the REWH available, and how does it compare with the supply and return temperatures of the DES?
- **Availability** – how reliably and when is the REWH available compared with the DES energy requirements on an hourly and seasonal basis?

For any given REWH resource the above design fundamentals have to be evaluated and optimized in the context of economic and environmental trade-offs. In addition, the longevity of the resource must be assessed, both from the standpoint of long-term physical access to the resource (e.g., the continued operations of an industrial plant providing waste heat) as well as economic access (continued economic attractiveness of the price of the resource).

Temperatures

A pervasive issue relative to tapping renewable and waste heat sources is the temperature of the resource compared with the supply and return temperatures of the DES network. Some resources, such as biomass, are fuels that can be used to produce whatever temperature is required. However, with lower district heating (DH) operating temperatures a greater range of REWH sources becomes available. The figure below shows representative temperatures for examples of REWH resources.
This figure is not exact, and certainly exceptions exist, but it gives the reader a quantitative illustration of the characteristics of these resources:

- Given the multiplicity of industrial waste heat sources, only a range is given for simplicity of presentation.
- A broad band of geothermal hot water temperatures is shown because such resources can vary significantly from one site to another.
- The thermal efficiency of engine CHP is increased if the DH temperatures are low enough to recover heat from jacket water and lubricating oil as well as the relatively high-temperature exhaust gas.
- Lower DH temperatures make it possible to produce useful heat with lower-cost flat-plate solar collectors in comparison with higher-cost evacuated tube collectors. (The efficiency of evacuated tube collectors in generating higher temperatures is substantially better than that of flat plate collectors.)
- For thermal sources that require a heat pump, the temperature boost from the heat pump is shown in grey and added to the source itself. The efficiency of these technologies is significantly affected by the required temperature lift, which should always be kept to the minimum required for highest efficiency. While some consider heat pump schemes to represent renewable energy, the reality is that sources such as groundwater or sewage effluent are a means of increasing the efficiency with which electricity is converted to thermal energy. Unless and until electricity grids are decarbonized, such heat pumps systems cannot truly be considered renewable.
REWHR resource temperatures must be compared to the supply and return temperatures of district heating distribution systems. There is a strong trend toward reducing district hot water supply and return temperatures. The evolution of district heating has been characterized in terms of “generations” -- with the first being steam, the second being hot water systems supplying (at peak conditions) >100°C (212°F), the third being hot water systems supplying 80-100°C (176-212°F), and the fourth being systems supplying less than 65-75°C (149-167°F). As district heating temperatures are reduced, the major concern is with the potential for legionella in the DHW, particularly during summer operations.

In this report we will use a somewhat different nomenclature than the categories outlined above regarding the four “generations.” The table below summarizes peak supply temperatures (and steam pressures, as appropriate) for five DH system types. The figure below illustrates a range of these peak supply temperatures as well as typical return temperatures.

<table>
<thead>
<tr>
<th>Steam</th>
<th>Peak Supply Temperature</th>
<th>Steam Pressure</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>F</td>
<td>barg</td>
</tr>
<tr>
<td>High pressure</td>
<td>194</td>
<td>381</td>
<td>13.8</td>
</tr>
<tr>
<td>Low pressure</td>
<td>126</td>
<td>259</td>
<td>1.4</td>
</tr>
<tr>
<td>High temperature</td>
<td>120</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>Medium temperature</td>
<td>100</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>Low temperature</td>
<td>70</td>
<td>158</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hot water</th>
<th>Peak Supply Temperature</th>
<th>Steam Pressure</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>F</td>
<td>barg</td>
</tr>
<tr>
<td>High temperature</td>
<td>120</td>
<td>248</td>
<td></td>
</tr>
<tr>
<td>Medium temperature</td>
<td>100</td>
<td>212</td>
<td></td>
</tr>
<tr>
<td>Low temperature</td>
<td>70</td>
<td>158</td>
<td></td>
</tr>
</tbody>
</table>
One critically important factor when considering the temperature scheme is the understanding of temperature duration and the fact that peak supply temperatures in most systems only have to occur for a few hundred hours per year. Hot water systems are usually designed to reduce temperatures during off-peak times, thereby further facilitating use of REWH.

Resources can be separated into the following groups depending on the specific annual temperatures of the resource:

1. High grade sources have reliably high temperatures that always exceed the DES supply temperature. These sources can be used directly whenever it is available.
2. Low grade sources have lower temperatures that are sometimes or always insufficient relative to the DES supply temperature but always sufficient relative to the DES return temperature. If the temperature of the source falls below the DES supply temperature, the temperature must be polished (increased for heating or decreased for cooling) with other energy sources.
3. Below grade sources always have temperatures lower than the return temperature in the DES. These sources must be upgraded with a heat pump.

As long as the temperature of the REWH is higher than the return temperature in the DES (heating mode, opposite for cooling) the resource can be used directly. When the temperature is lower than the return temperature in the DES (heating mode, opposite for cooling), either the temperature must be upgraded with a heat pump or the existing DES (or the design of a new...
DES) must be modified in order to use the REWH. In considering temperatures it is also important to note that a further temperature differential between the resource and DES temperature generally is required due to the use of heat exchangers.

When the temperature of the REWH is lower than the return temperature in the DES (heating mode, opposite for cooling), an existing DES could adapt in a number of ways, e.g.:

- Make improvements to achieve a lower return temperature (in a heating system) or a higher return temperature (in a cooling system). Typically this could include minimizing bypasses in the system, improving process control and coil performance at customer buildings, or other steps. Such measures have costs, and could be funded either directly by the DES utility (if determined to be cost-effective on a life cycle basis in comparison with other options) or indirectly by encouraging customer investments to improve delta T.
- Curtail the flow or the temperature to achieve low return temperature. This approach requires careful consideration and testing before implementation to ensure continued customer comfort.
- Find other low grade heat sinks to further reduce the DH return temperature, such as use of the return water for preheating, snow melting, etc.

If adaptation is not possible or insufficient, the use of REWH can be enabled by replacing the high temperature DH system (often a steam system) with a lower temperature system.

Availability

Another critical aspect of a REWH is its availability on an hourly or seasonal basis. Some resources, such as solar and wind, are intermittent and therefore are not dispatchable. Further, the seasonal distribution of the resource may be counter to the seasonal distribution of the thermal requirement. The hourly availability of resources such as industrial waste heat is tied to the operating hours of the industrial facility, and may be subject to interruptions.

With a thorough understanding of availability, the capacity of the REWH can be properly sized. Typically, renewable energy sources have lower operating cost but have higher capital costs and lower turndown capability (although some exceptions exist, such as bioliquids).

Sizing a REWH source that is intermittent and/or interruptible requires careful optimization. One option is to undersize the REWH source and continuously polish with a conventional energy source. Integration of the REWH source with thermal energy storage offers greater flexibility. The type of thermal storage depends on the availability pattern of the resources, and may be daily or seasonal storage.

Business Issues

There are three fundamental business drivers for any change to an existing DES:

- Load growth.
- System optimization and cost reduction.
- Reduction in environmental emissions.
Increased customer load may require additional production capacity, providing an opportunity to integrate REWH. Alternatively, a REWH may offer the potential to reduce life cycle costs compared to current energy sources. Although rarely the key driver, goals for reduction in GHG or other emissions may also affect the decisions on modification of existing systems.

Financing a REWH project is made more challenging because future energy prices are uncertain. This includes the likelihood that waste heat or other resources that are currently free or very low cost may become more expensive. In assessing options it is useful to consider the benefits of a given change relative to the flexibility to respond to new technical opportunities or changing price conditions.

The customer contract is the most important document for communication between the DES system operator and its customers because it can influence the performance of the building system in ways that can help or hinder the total efficiency and cost-effectiveness of the DES. This becomes even more critical with low temperature district heating systems. It is important to incorporate economically transparent price signals in the customer tariffs. Price signals in the contract can influence technical performance, for example by encouraging high delta T and discouraging low delta T, thereby reducing distribution losses and improving energy conversion in the plants.

**Optimization Analysis**

Based on fundamental design criteria REWH resources can be grouped into the following categories:

<table>
<thead>
<tr>
<th>Temperature Characteristic</th>
<th>High grade</th>
<th>Low grade</th>
<th>Below grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispatchable</td>
<td>Biomass, Bioliquids, Biogas, Municipal solid waste, Geothermal heating*</td>
<td>Geothermal heating*</td>
<td>Geo-exchange</td>
</tr>
<tr>
<td>Correlated with DES load</td>
<td>Flue gas heat recovery</td>
<td>Chiller heat recovery</td>
<td></td>
</tr>
<tr>
<td>Site-specific annual pattern</td>
<td>Deep water cooling*</td>
<td>Sewage heat recovery</td>
<td></td>
</tr>
<tr>
<td>Intermittent</td>
<td>Wind</td>
<td>Concentrating solar</td>
<td>Industrial waste heat*</td>
</tr>
</tbody>
</table>

* Deep water cooling* refers to the deep water cooling system, which is temperature correlated with deep water.
Temperatures

Historically, conventional hydronic building heating systems were designed for supply/return temperatures of 82/71°C (180/160°F). There is a trend toward reduced temperatures for exactly the reasons addressed in this report. On the other hand, a balance must be achieved because designing for higher temperature systems helps improve economics due to the costs of additional heat transfer area in equipment for lower temperature systems.

Technically, it is possible to reduce supply temperatures for building space heating (SH) systems down to near the desired indoor air temperature (20°C or 68°F). There is a trend in Europe toward reducing SH system supply temperatures down to the range of 45-55°C (113-131°F).

The risk related to the Legionella bacteria, amoebae and other microorganism growth in domestic hot water (DHW) systems is the key limitation in reducing district heating temperatures. Beyond the supply temperatures, the return temperatures from building SH and DHW systems are crucial variables.

Whenever there is a temperature limitation of the REWH source, the DES supply temperature duration curve (temperature program) should be given careful consideration. In general, a low DES supply temperature minimizes distribution heat losses, but there may be an economic trade-off because a reduced delta T increases costs for water distribution, and for building systems if building system improvements have to be implemented.

Evaluation and optimization for utilization of a low- or below-grade REWH source should focus both on the DES supply and return temperature vs. the REWH source temperature. By definition, a low-grade REWH source is sometimes or always insufficient relative to the DES supply temperature but always sufficient relative to the DES return temperature. Given the fundamental physics of coils and heat exchangers, and provided there are no bypasses and/or flow control issues, a higher supply temperature should result in a lower return temperature. This means that there may be situations where it could be beneficial to keep a relatively high DES supply temperature throughout the year in order to achieve a lower return and therefore facilitate additional use of the low grade source. This will also reduce costs for flow distribution and building systems but there is an economic trade-off with respect to higher heat losses in the distribution piping system. An alternative strategy is to polish the DES supply temperature only as required for peak loads.

For an existing DES this has to be carefully tested and integrated. In practice, some systems will experience a rise in return temperature in conjunction with the supply temperature due to poor process control and/or bypasses in the system.

A below-grade REWH source always has a temperature lower than the DES return temperature and must utilize heat pumps to further extend the temperature range for heat recovery. In using heat pumps, it is of utmost importance to minimize the temperature lift (difference between the source temperature and the goal temperature) to achieve high efficiency.
Resource Availability

Resources can be grouped in the following categories: dispatchable; correlated with DES load; site-specific annual pattern; and intermittent.

Dispatchable REWH sources typically have no or only minor integration issues when connecting the source with a DES. Examples of dispatchable REWH sources are bio-energy, municipal solid waste, geothermal heating and geo-exchange. The main general technical concern for implementing a dispatchable REWH source is the control integration between the source and other energy sources within the DES.

Examples of REWH sources that correlate with the DES load are flue gas heat recovery and chiller heat recovery. For these sources it is critically important to understand the load pattern when sizing the REWH source. Chiller heat recovery requires a complete understanding of the daily and seasonal load pattern curves for both the DES heating and cooling systems in order to evaluate the overlap of the thermal loads.

Other REWH sources, such as deep water cooling and sewage heat recovery, have a site-specific pattern of availability relative to resource temperature.

Examples of intermittent REWH sources are wind, solar thermal and industrial waste heat recovery. A typical characteristic for these sources is the unreliable nature of the resource supply. As a result, careful consideration must be given to readily available backup from other sources for critical loads/customers.

One thing all sources have in common is the usefulness of integrating them with thermal energy storage. Thermal storage facilitates maximum usage of REWH sources when those sources are available, and allows use of this stored energy when required, thereby maximizing use of sustainable energy sources.

General Recommendations

Confirmation of Goals. Whether the DES system is new or existing, it is appropriate to start any analysis of integration of REWH by confirming the goals to be achieved and the relative emphasis that should be placed on each goal. Goals may include, for example:

- Reduction in emissions of greenhouse gases (GHG) or other environmental impacts.
- Reduction in costs.
- Increased flexibility to respond to future changes in supplies and/or prices of fossil fuels.
- Local economic development.
- Public relations.

DES Loads and Temperatures. It is essential to model the DES loads, ideally on an 8760 hour basis, relative to both energy and temperature. In an existing DES system operating data can inform this analysis. For integrated district heating and cooling systems it is especially critical to understand when heating and cooling loads occur simultaneously or within a 24 hour period.
To the extent that data allows, it is useful to examine how each of the customers contributes to the delta T performance of the system. If existing buildings are to be served with a low temperature hot water system, it is important to test each building, or a sampling of representative buildings, at low supply temperatures to determine return temperature performance. For a new DES, the choice of DES temperature regime requires a thorough comparative life cycle economic analysis. For new buildings, use of underfloor or in-wall heating systems can help reduce the temperature requirements of the customers.

**Resource Assessment.** REWH resources must be assessed relative to:

- Quantity of energy potentially available.
- Temperatures.
- Availability and reliability of energy supply, both in the near- and long-term.
- Capital costs.
- Near-term resource price.
- Long-term potential for resource competition that would drive up the price of the resource.
- Other operation and maintenance costs.
- Maturity of the required technologies.

**Integrated Assessment.** There can be significant benefits in combining multiple REWH sources in a DES to the extent that the temperature and availability patterns of the sources complement each other. On the other hand there is also a risk in combining REWH sources to the extent that one source could displace another if the integration has not been thoughtfully considered.

**Monitoring, Control and Dispatch.** In any system involving electricity production and/or consumption, and/or systems incorporating multiple thermal sources, a predictive economic dispatch model of the production sources is essential to provide guidance for the plant operators. Dispatch merit order may also take into account environmental attributes. It is important to note that while some plant operations could be automated, the most important decisions should be made by trained, licensed human operators. Instrumentation redundancy and data collection should be planned at the onset of a project. Real time software simulations of the network helps minimise heat losses and pumping energy consumption to ensure the lowest possible environmental impact.

**Resource Contracts.** For any given REWH project, transparency is a key to ensure win-win solutions for the seller and buyer of thermal energy. Price structures should take into account the temperature of the thermal energy as well as its availability and reliability. For district energy systems procuring thermal energy from multiple outside sources it is important to develop a policy and operational strategy for right of precedence for energy delivery into the district scheme.

**Customer Contracts.** It is important to ensure an optimized temperature difference between DES supply and return (delta T) in order to maximize efficiency and realize thermal storage design capacity. If new buildings are to be served, it is useful to provide building system design
guidance and review to ensure that the system provides a good delta T. Economically transparent price signals should be incorporated in the customer tariffs.

**Life Cycle Economic Analysis.** Good decisions about integrating REWH in a DES require a thorough comparative analysis of the capital and operating costs of options relative to: energy resources; distribution systems; building substations; and building heating/cooling systems. The task is made more complex because the analysis should not only address the near term but also future growth and evolution of the system. In this regard it is important at the outset to assess the potential energy resources in the community and how price and technology trends might affect the future viability of that resource for the DES.

**Resource-Specific Recommendations**

The report provides resource-specific considerations for each REWH and addresses technical and economic parameters, lessons learned and key issues for integration with a DES.

**Bioenergy.** When planning a biomass project, it is important to focus attention on ensuring a supply of fuel of sufficient quality and quantity. If fuel is to be procured from outside suppliers it should be done under very tight contracts relative to fuel quality, particularly moisture, particle size and non-combustibles. Fuel should be purchased based on the energy contained in the fuel or on a dry basis (price per dry ton of fuel). Additional processing may be required to avoid materials handling problems due to oversize particles. Depending on location, seasonality of supply can be a big issue, so adequate fuel storage is important. Consideration should be given to the long-term potential for price increases due to increased competition for bio-fuels.

**Municipal Solid Waste.** Generally, the key challenges with integrating municipal solid waste are the distance between the plant and loads, and “Not In My Back Yard (NIMBY)” public opposition. In some countries, such as the UK, municipal waste is commonly incinerated without heat recovery, so the primary challenge relates to the costs of the infrastructure to convey the waste heat to users. In other countries, such as the USA, the NIMBY problem is significant, in which case it is helpful that Waste to Energy systems provide a good complement to recycling programs, and have positive environmental attributes when the avoidance of fossil fuel combustion for thermal and electricity production are counted.

**Geothermal Heating.** A key economic issue with geothermal energy systems relates to the relatively large initial investment in drilling and the technical risks of not finding enough hot water. It is also critically important to have an adequate understanding of the long-term flow and temperature characteristics of the geothermal resource.

**Solar Thermal.** Solar thermal availability generally has an inverse relationship to the heating load needs. This is true not only on a daily level but frequently also on a seasonal level. Hence, hot water thermal storage helps maximum utilization. When sizing a solar thermal system for integration with a DES, a low district heating supply temperature is beneficial since collector performance deteriorates with higher temperatures. Thermal energy storage is essential for optimized use of solar heat.

**Wind.** Wind is relevant to DES primarily in the context of integration of DES with power grids as a power load balancing strategy. Hot water systems can absorb large quantities of electricity
and convert the energy to storable hot water by using heat pumps and/or immersion heaters. As with solar energy, thermal energy storage is a critical element in a DES wind strategy.

**Deep Water Cooling.** Prior to design it is important to implement a monitoring program to determine lake or sea water temperatures at various depths at the project site. Deep water cooling is heavily dependent on a stable and predictable range of the maximum depth of the thermocline and a large enough water volume below this depth.

**Heat Pump Technologies.** When sizing a heat pump system for DES integration, a low temperature difference between the heat source and heat sink is essential since heat pump efficiency deteriorates with a high temperature difference. Commercially available heat pumps have a limited supply temperature, so lower DES temperatures could be a requirement for effective DES integration. Hot water supply temperature plays a major role in heat pump systems since the efficiency decreases with high supply temperature.

When evaluating geo-exchange it is important to carefully consider the following technical and economic parameters:

- Hydrogeological and geochemical description of the site.
- Environmental regulatory acceptance.
- Location and space requirements.

Closed loop systems require multiple boreholes and, if not sized properly, may raise underground temperatures over time, cutting efficiencies in the cooling cycle. Open loop geothermal requires fewer wells but there are more issues with corrosion, particulate filtering and potential groundwater contamination. Additional discussions will also be necessary with the environmental regulatory agencies to gain approvals.

When sizing a chiller heat recovery (HRC) system it is essential to adequately understand the 8760 hour patterns of cooling and heat loads, including their overlap. There must be coincident cooling and heating loads or thermal storage is required.

A key consideration when integrating sewage or sewage treatment effluent is ensuring adequate sewage flows vs. DES heat demand variability. Thermal storage may be a useful optimization technology for optimizing use of these resources. If untreated sewage is used, it is critical to design for easy maintenance to ensure clean heat exchange surfaces.

**Industrial Waste Heat Recovery.** The key financial risk is related to the capital investment in the piping system to link the industrial source with the DES. In designing the business arrangement between a district energy system and an outside industrial supplier of waste heat, it is essential for the contract to incorporate a transparent and clear picture of economic risks and rewards. Business risk analysis should address short term consequences of sudden shutdown as well as long term costs to finance alternative base load supplies.

Important technical issues to be given careful consideration when evaluating industrial waste heat recovery are:
Corrosion and oxidation reactions are accelerated dramatically by temperature increases. Advanced alloys or composite materials must be used at higher temperatures.

If the source is intermittent, the heat exchanger (HEX) may be exposed to both high and low temperatures and it becomes important to ensure that the HEX material does not fatigue due to thermal cycling.

**Flue Gas Heat Recovery (FGHR).** When integrating FGHR into a DES it is important to:

- Design the system based on flue gas latent heat content, temperature and dew point versus available DES return temperature, because available waste heat decreases with temperature (especially if flue gas condensation cannot be achieved).
- Size the FGHR based on the operating pattern of the boiler supplying the flue gas.
- Ensure that the boiler is operating as the DES base load to maximize heat recovery.
- Develop a good understanding of physical and chemical impact of gas streams on heat exchangers (heat exchangers designed from inappropriate low-cost materials will quickly fail due to chemical attack).
- Design for adequate emissions control of condensing heat recovery water and air effluent.

Integrating flue gas heat recovery in a CHP system using the DES as the heat sink requires special consideration from an economic perspective. With steam cycle CHP, more electrical power can be generated and higher efficiency attained with a large heat sink and low temperature. However, introducing flue gas heat recovery as a heat source for the DES can reduce the available heat sink and hence the electrical power generation. This may still be a good solution depending on fuel prices compared with the market value of electricity, but nevertheless it is a key issue that must be considered.
1 General Preface Annex X 2011 - 2014

1.1 Introduction

The International Energy Agency (IEA) was established in 1974 in order to strengthen the cooperation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climatedestabilising carbon dioxide.

At the 2005 Gleneagles G8 an important role was given to the IEA in advising on alternative energy scenarios and strategies aimed at a clean, clever and competitive energy future. Two years later, at the Heiligendamm G8, it was agreed that “instruments and measures will be adopted to significantly increase the share of combined heat and power (CHP) in the generation of electricity”. District Heating and Cooling is an integral part of the successful growth of CHP: heat networks distribute what would otherwise be waste heat to serve local communities. The IEA is active in promoting and developing knowledge of District Heating and Cooling: while the DHC programme itself is the major global R&D programme, the IEA Secretariat has also initiated the International DHC/CHP Collaborative which assesses global markets and policies for these important technologies.

The IEA’s latest CHP report, "Cogeneration and District Energy: Sustainable energy technologies for today…and tomorrow", released at COGEN Europe meeting in Brussels on 21 April 2009, identifies proven solutions that governments have used to advance CHP and district energy, setting out a practical “how to” guide with options to consider for design and implementation. The report concludes that these technologies do not need significant financial incentives; rather they require the creation of a government ‘champion’ to identify and address market barriers. This makes CHP and district energy ideal investments at a time of tight budgets.

The CHP report follows the IEA’s first report from March 2008, "Combined Heat and Power: Evaluating the Benefits of Greater Global Investment". There are also 11 “Country Scorecards” that evaluate different countries’ success in achieving increased use of CHP and DHC. In November 2009, the IEA joined with the Copenhagen District Energy Summit to issue the first Global District Energy Climate Awards in order to recognize communities that have embraced district heating and cooling as a vital sustainable energy solution.

1.2 The Major International R&D Programme for DHC/CHP

DHC is an integrative technology that can make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.

The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating and cooling.
The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling carbon-intensive electrically-based air-conditioning, rapidly growing in many countries, can be displaced.

As one of the IEA’s ‘Implementing Agreements’, the District Heating & Cooling programme is the major international research programme for this technology. Active now for more than 25 years, the full name of this Implementing Agreement is ‘District Heating and Cooling including the integration of Combined Heat and Power’. Participant countries undertake co-operative actions in energy research, development and demonstration.

1.3 Annex X

The tenth three-year period (Annex X) of the IEA R&D Programme on District Heating and Cooling, including the integration of Combined Heat and Power was implemented between 1 May 2011 and 30 April 2014. Annex X was started with the participation of Canada, Denmark, Finland, Germany, Norway, South Korea, Sweden, United Kingdom, and the United States of America.

Below you will find the Annex X (2011 – 2014) research projects undertaken by the Implementing Agreement “District Heating & Cooling including the Integration of Combined Heat and Power”.

<table>
<thead>
<tr>
<th>Project title</th>
<th>Company</th>
<th>Ref. Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Maintenance Strategies for District Heating Pipe-lines</td>
<td>• SP Technical Research Institute of Sweden</td>
<td>IEA-X-C-001</td>
</tr>
<tr>
<td></td>
<td>• KDHC - Korea District Heating Corp.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Statkraft Varme AS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• IMA Materialforschung und Anwendungstechnik GmbH</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• FVB Sverige AB, Sweden</td>
<td></td>
</tr>
<tr>
<td>Towards Fourth Generation District Heating: Experiences with and Potential of Low Temperature District Heating</td>
<td>• DTU, Denmark</td>
<td>IEA-X-C-003</td>
</tr>
<tr>
<td></td>
<td>• BRE, UK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Scottish &amp; Southern Energy, UK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Halmstad University, SE</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Dresden University of Technology</td>
<td></td>
</tr>
<tr>
<td>Development of an Universal Calculation Model and Calculation Tool for Primary Energy Factors and CO2</td>
<td>• SINTEF Energy Research, Norway</td>
<td>IEA-X-C-004</td>
</tr>
<tr>
<td></td>
<td>• SP Technical Research Institute, Sweden</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Korea District Heating Technology</td>
<td></td>
</tr>
</tbody>
</table>
1.4 Benefits of Membership

Membership in this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

- DHC is already a mature industry.
- DHC is well established but refurbishment is a key issue.
- DHC is not well established.

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organizations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include sharing knowledge and ideas and opportunities for further collaboration. New member countries are very welcome – please simply contact us (see below) to discuss.

1.5 Information

General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website www.iea-dhc.org or from:

<table>
<thead>
<tr>
<th>Operating Agent</th>
<th>IEA Secretariat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Andrej Jentsch</td>
<td>Energy Technology Policy Division</td>
</tr>
<tr>
<td>AGFW Projekt Company</td>
<td>P Marc LaFrance</td>
</tr>
<tr>
<td>Stresemannallee 30</td>
<td>9, Rue de la Federation</td>
</tr>
<tr>
<td>60596 Frankfurt, Germany</td>
<td>75015 Paris</td>
</tr>
<tr>
<td>Tel.: +49 69 6304 344</td>
<td>France</td>
</tr>
<tr>
<td>Fax: +49 69 6304-391</td>
<td>Tel.: +33 (0) 140576738</td>
</tr>
<tr>
<td>E-mail: <a href="mailto:iea-dhc@agfw.de">iea-dhc@agfw.de</a></td>
<td>Fax: +33 (0)1 40 57 65 09</td>
</tr>
<tr>
<td></td>
<td>E-mail: <a href="mailto:Marc.LAFRANCE@iea.org">Marc.LAFRANCE@iea.org</a>&gt;</td>
</tr>
</tbody>
</table>
2 Introduction

2.1 Purpose
A key argument in favor of district energy from a policy perspective is its ability to facilitate use of renewable energy and waste heat resources (REWH). These low- or no-carbon energy sources include bioenergy, solar thermal, geothermal hot water, geothermal heat pumps, industrial waste heat, municipal waste combustion, municipal waste heat (landfill gas, sewage effluent), and deep water cooling.

Renewable electricity used to power heating or cooling systems are not considered in this report except in the case of wind, which offers some unique value-added economic benefits due to the ability to generate additional revenue for district energy systems by providing power grid balancing services.

Combined heat and power (CHP) is not a resource but rather a range of conversion technologies which convert renewable or non-renewable resources into power and thermal energy. For this reason, and given that the unique issues which arise with integration of CHP have been addressed in other reports, this report addresses CHP only briefly.

This report is intended to guide evaluation of options for integrating renewable energy and waste heat with existing or potential district energy systems. The report addresses economic, design and operational issues including fundamental issues relating to operating temperatures and resource availability.

2.2 Acknowledgments
This report was prepared by FVB Energy Inc. (USA) with expert support and assistance from FVB Sverige AB (Sweden). Ever-Green Energy (USA) provided case study data relating to their solar thermal installation. We gratefully acknowledge the following members of the Experts Group that was appointed by the IEA as they also played a key role in guiding, developing, and providing feedback to the project:

- Ben Watts (Cofely, United Kingdom)
- Michael Wiggin (Public Works and Government Services Canada, Canada)
- Jan Elleriis (Metro Copenhagen Heating Transmission Co., Denmark)
- Heiko Huther (AGFW, Germany)
- Robert Smith (RMF Engineering, United States)

Other members of the Experts Group included:

- Matti Nuutila (Energia, Finland)
- Nam Woong Kim (District Heating Corporation, Korea)
- Jung Hwan Hong (District Heating Corporation, Korea)
- Morten Fossum (Statkraft Värme AS, Norway)
2.3 Report Structure
Following this introduction:

- Section 3 provides a brief overview of the case studies that will be used in the report. The intent of the case studies are to: provide examples of the integration of REWH resources into district energy systems; illustrate key issues in integrating such resources; and describe strategies for addressing these issues.
- Section 4 describes key potential REWH resources.
- Section 5 presents a framework for categorizing and evaluating REWH resources.
- Section 6 presents an approach to analyzing key issues relating to the integration of REWH resources into district energy systems, with examples drawn from the case studies.
- Section 7 concludes the report with a discussion of recommended strategies for integrating REWH in district energy systems. The recommendations address cross-cutting strategies (applicable to a range of resources) as well as resource-specific design and economic issues.

Complete case studies are provided in the Appendices.
3 Case Studies

Case studies were developed to illustrate a range of examples of integration of REWH in district energy systems (DES), illuminate key design issues associated with such integration, and describe solutions to addressing these issues.

3.1 Individual Case Studies

Figure 1 provides an overview of the individual case studies that will be referenced in the report. Full case studies are provided in Appendix 1. For the most part, these case studies describe schemes which have been implemented, although several of the case study systems are still in construction. In the case of District Energy St. Paul, two case studies are presented: a brief overview describing the entire DES; and a detailed case study of the solar thermal installation.

![Figure 1. Relevance of Case Studies for each REWH Resource or Storage Technology](image-url)
3.2 Country Transitions to REWH

District energy infrastructure has enabled relatively swift national transitions in primary energy consumption. This section briefly describes how the entire district heating sectors in Sweden and Denmark have transitioned from fossil fuels to predominantly REWH.

3.2.1 Sweden

Since 1980 Sweden has accomplished a dramatic shift in its energy sources, largely facilitated by district heating. Between 1980 and 2008, district heating grew by 76%. Figure 2 shows the evolution of district heating fuels/energy sources in district heating systems. Sweden drastically reduced use of oil, shifting from 89% oil dependency in 1980 to 7% in 1990. By 1990, Swedish district heating systems had transitioned to 32% renewable energy sources, growing to 77% by 2008. The increases in total consumption during the period 1985 – 1989 were due to extremely cold weather.

![Figure 2. Transition of Swedish District Heating Fuels from Oil to Renewable Energy, 1980-2008](image-url)
3.2.2 Denmark

After the energy crisis in the 1970s a massive development of district heating from CHP took place and initially production plants were converted from oil to coal. In 1979, a new heat supply act was implemented in Denmark with the goal of introducing mandatory district heating as well as a new infrastructure for domestic natural gas.

Climate policies became the key driver in the 1990’s, when the extensive DES schemes reached national coverage. New targets were adopted for the replacement of coal with biomass at large-scale CHP plants as a new means for reducing CO2 emissions.

Figure 3 shows the significant reductions in fossil fuel use in the Danish DH sector since 1980.\(^2\) As of 2011, over 61% of Danish citizens were served by DH.\(^3\)

![Figure 3. Transition of Danish District Heating Fuels, 1980-2010](image-url)
4 Renewable and Waste Heat Resources

4.1 Introduction

There is a broad array of potential REWH resources that could be integrated into DES. Some sources, such as biomass, can be directly combusted to produce heat only, or heat and power in a CHP facility. Biomass resources can also be converted into gaseous or liquid fuels in systems designed for production of heat and/or power. Gases with energy content are also generated as a byproduct of other processes, such as decomposition of organic wastes in landfills. A range of technologies are able to produce energy from municipal solid waste. In some locations heat from deep in the earth is available at or near the surface which can be used to produce heat and/or power. Heat may be generated as a byproduct of industrial processes, which can be converted to useful energy with a heat exchanger. Natural sources of thermal energy, such as earth temperatures or byproducts of municipal processes such as sewage treatment, can be used to increase the efficiency of production of heat with electricity through the use of heat pumps. Earth temperatures can also be used as heat sink to increase the efficiency of electrically-driven cooling.

4.2 Combined Heat and Power (CHP)

Many studies have addressed the integration of CHP with DES. Because this report is concerned with the impact of district heating temperatures on the potential to use waste heat, we will briefly address the potential impact of lower district heating temperatures on the efficiency and economics of CHP. In steam-cycle or combined-cycle CHP, the lower the temperature of the recovered heat, the higher the output of electricity. For example, as illustrated in Figure 4, at 80°C (176°F) about 13 units of heat can be recovered for every unit of electricity production reduced as a result of the heat recovery. At 100°C (212°F) this “extraction COP” drops to about 10, and at 120°C (248°F) only about 8 units of heat can be recovered for every unit of electricity production reduced. Thus, a lower heating temperature helps make CHP more feasible because it allows higher production of electricity, which has a higher market value than heat.
4.3 Bioenergy

4.3.1 Introduction

Biomass is a very diverse category of materials that includes wood residues, organic wastes, crop residues, crops grown specifically for energy production, animal wastes (manure) and other organic matter. Some analysts include municipal solid waste (MSW) as biomass, but in this report we will address MSW separately.

Biomass can be converted into useful energy or chemicals through a range of processes including direct combustion, transesterification, fermentation, anaerobic digestion and pyrolysis. The following discussion focuses on three categories of bioenergy:

- Biomass – direct combustion of biomass.
- Bioliquids – liquid fuels made from biomass.
- Biogas – gaseous fuels made from biomass.

4.3.2 Biomass

4.3.2.1 Overview

Direct combustion is the most common method of converting biomass resources into thermal energy and/or electricity. Thermal energy in the form of steam or hot water can be produced...
through combustion of biomass in a boiler. Biomass can also be co-fired with coal as a supplementary energy source. Electricity can be generated with biomass in a steam turbine power plant, with or without CHP.

4.3.2.2 Biomass Fuels

Woody biomass resources are by far the most commonly utilized solid biomass feedstock. Woody biomass systems may be designed to handle wood chips (Figure 5), bark (Figure 6), sawdust (Figure 7) or other types of woody materials. Woody biomass can also be refined through pelletizing, a process in which the wood is dried to approximately 10% moisture, then ground and finally compressed into dense pellets. This produces a homogenous fuel material with a high energy density in cylindrical shapes with a 5-8 mm diameter (Figure 8).

Figure 5. Debarked and Screened Chips
Figure 6. Bark

Figure 7. Sawdust
There is increasing interest in processing biomass to facilitate its use as a co-fired fuel in existing coal boilers. Torrefaction is a thermo-chemical process conducted in the absence of oxygen, during which biomass partially decomposes, giving off volatiles and giving the remaining solid as a final product (Figure 9). An advantage of torrefaction is that different types of feedstocks have quite similar physical and chemical properties after torrefaction, which is a very attractive feature relative to process optimization and control.
The coal-like characteristics of torrefied biomass make it possible to blend it with coal in much higher proportions than are achievable with industrial wood pellets. Industrial pellets are typically co-fired with coal at a rate of approximately 5 to 20%, whereas with torrefied biomass co-firing rates of 40% may be achievable.\(^8\)

Processing biomass to produce pellets or torrified fuel requires not only additional economic costs but also expenditure of energy.

### 4.3.2.3 Biomass Combustion

The two principal types of direct combustion boiler systems are fixed-bed (stoker) and fluidized-bed systems. In a fixed-bed system, the biomass is fed onto a grate where it combusts as air passes through the fuel, releasing the hot flue gases into the heat exchanger section of the boiler to generate steam or hot water. A fluidized-bed system instead feeds the biomass into a hot bed of suspended, incombustible particles (such as sand), where the biomass is combusted to release the hot flue gas.

Although most direct combustion CHP systems generate power using a steam-driven turbine, it is also possible to drive turbines using other working fluids. One emerging application is the coupling of an Organic Rankine Cycle (ORC) power generator to a REWH source. ORC technology uses a low-temperature (approximately 85°C and greater), low-pressure energy source to heat a thermal oil. The heat source could be any of a range of heat sources, e.g., biomass combustion, industrial waste heat, solar collectors, geothermal hot water, etc. The heat is then used to boil a compressed working fluid that has a lower boiling point than water (such as pentane or other volatile organic compound). The pressurized vapor then drives a turbine-generator to produce electricity.

Figure 10\(^9\) illustrates the ORC process:

- A heat source heats thermal oil in a closed circuit. Although this graphic indicates the heat source as gas turbine exhaust, as noted above it could be any of a range of low temperature heat sources.
- The thermal oil evaporates an organic working fluid in a heat exchanger system (pre-heater and evaporator).
- Organic vapor expands in the turbine, producing mechanical energy, which is used to produce electric energy through a generator.
- The vapor is then cooled and condensed in a closed condenser loop. The condenser water warms to about 80-90°C (176-194°C and can be used for different applications requiring heat.
- The condensed organic fluid is pumped back into the regenerator to close the circuit and restart the cycle.
The electrical efficiency of an ORC depends on the temperature levels of evaporator and condenser. An increase in evaporator temperatures and/or decrease in condenser temperatures will give higher efficiencies. Although the electrical efficiency of ORC is lower than a steam turbine, the low temperature and pressure of the system typically allows for lower operating requirements and costs (e.g., labor).

Somewhat similar to the ORC is the Kalina cycle. Instead of using a volatile organic chemical as a working fluid, it uses a mixture of water and ammonia. Design challenges associated with a Kalina cycle installation are described in the case study on Husavik, Iceland.

### 4.3.3 Bioloquids

#### 4.3.3.1 Overview

Liquid biofuel is typically a bioalcohol (ethanol fuel), a bio-oil (biodiesel) or a straight vegetable oil. Ethanol, the most widely used biofuel, is produced through fermentation and is used as an alternate fuel or as an octane-boosting, pollution-reducing additive to gasoline. Since it is a transportation fuel, ethanol is not relevant to this study.

Biodiesel, a clean burning alternative fuel produced from vegetable oils and animal fats through a chemical process called transesterification, can be used in diesel engines with little or no modifications. Biodiesel is potentially relevant to this study. The most common sources of oil for biodiesel production in the U.S. are soybean oil and yellow grease (primarily recycled cooking oil from restaurants).
Blends of biodiesel and petroleum diesel are designated with the letter “B,” followed by the volumetric percentage of biodiesel in the blend: B20, the blend most often evaluated, contains 20% biodiesel and 80% petroleum diesel; B100 is pure biodiesel. By several important measures biodiesel blends perform better than petroleum diesel, but its relatively high production costs and the limited availability of some of the raw materials used in its production continue to limit its commercial application.

Blends of 20% biodiesel and lower can be used in diesel equipment with no, or only minor, modifications, although certain manufacturers do not extend warranty coverage if equipment is damaged by these blends. Biodiesel can also be used in its pure form (B100), but may require certain equipment modifications to avoid maintenance and performance problems.10

Biodiesel can be combusted in a heat-only boiler, or used to fuel a combustion turbine or reciprocating engine to produce electricity and (in CHP designs) thermal energy. Changes in fuel nozzles and retuning of the combustion control system are generally required for conversion of a fuel oil boiler to biodiesel. Use of biodiesel as a substitute for natural gas in a combustion turbine has been successfully demonstrated at Princeton University (see case study).

Biodiesel production is a commercially proven technology. With favorable air emissions characteristics, biodiesel combustion is superior to petroleum diesel relative to air emissions.

4.3.4 Biogas

Gaseous fuels can be produced from biomass through two main types of processes, pyrolysis and anaerobic digestion.

4.3.4.1 Pyrolysis (Syngas)

Pyrolysis is the process of heating biomass at a high temperature without combustion, with no or a very limited amount of oxygen. The resulting gas mixture composed of carbon monoxide, hydrogen and CO2 is called syngas (from synthesis gas or synthetic gas) or producer gas. This process also produces a liquid oil and a solid char (which can be combusted or activated to make activated carbon).

In a close-coupled gasification system, the combustible gas is burned directly for space heat or drying, or burned in a boiler to produce steam or hot water. Alternatively, in a two-stage gasification system, tars and particulate matter are removed from the combustible gas, resulting in a cleaner gas suitable for use in a reciprocating engine, combustion turbine, or other application requiring a high-quality gas. Close-coupled biomass gasification-boiler systems are to a great extent a viable, commercially available technology. Two-stage gasification systems—in which the combustible gas is conditioned (cleaned) and then used in an engine, a turbine, or as a natural gas substitute—currently are in the developmental and demonstration stage.11

A number of companies specialize in medium to large-scale close-coupled gasification systems. In 2012 commercial operations began on a gasification system fed with local forest and sawmill waste to provide heat to the U.S. Department of Energy’s Oak Ridge National
Laboratory (Figure 11). Other industrial-scale heating systems operate using agricultural residues.

![Image](image_url)

**Figure 11. Biomass Gasification Facility at Oak Ridge National Laboratory**

Gasification system vendors are attempting to expand the technology options for use of syngas. For example, Nexterra and General Electric (GE) are jointly developing a process by which the low Btu syngas can be efficiently used by a reciprocating engine to generate electricity and have installed a facility at the University of British Columbia (UBC). The gasification process remains the same but instead of oxidizing the syngas exiting the gasifier, it is sent through a syngas conditioning system for use in the engine. The engine is also outfitted with heat recovery equipment to generate hot water. As of April 2014, the syngas engine installed at UBC has not yet achieved commercial operation.

**4.3.4.2 Anaerobic Digestion**

Anaerobic digestion produces a gas comprised primarily of methane (50%-80%) and CO2 (20%-50%). In the digestion process, bacteria degrade biological material in the absence of oxygen and release methane. The energy value of biogas is roughly proportional to the amount of methane present.

Anaerobic digestion can use almost any organic material as a substrate. A common form of biogas is landfill gas (LFG), which is generated naturally during the decomposition of municipal solid waste in the anaerobic conditions found within a landfill. By installing a collection system consisting of vertical or horizontal wells and piping connected to a blower, LFG can be extracted from a landfill to generate electricity and/or thermal energy. Most commonly, LFG is
used for electricity production. LFG consists of roughly 50% methane and 50% CO2. Biogas is also naturally generated during the treatment of wastewater at wastewater treatment plants (WWTP).

The harvesting of LFG or WWTP gas, which is already being generated for non-energy purposes, can play an important role in waste management because methane is 21 times more potent than CO2 as a greenhouse gas.

Biogas can be produced from a wide range of organic materials in anaerobic digestion facilities designed expressly for energy production. In addition to producing biogas, anaerobic digestion produces a low-odor nutrient-rich effluent which can then be used for fertilizer or bedding. An overview of the process is shown in Figure 12.

Digester gas can be burned in boilers to produce steam or hot water, and can be used directly in engines or turbines. In order to substitute directly for natural gas, digester gas must be cleaned up by removing CO2, trace contaminants, and any hydrogen sulphide it contains.

In addition to thermal and electricity production, biogas can be used as a transportation fuel. In Linkoping, Sweden, biogas is produced from household waste, animal waste and agricultural waste and is used to fuel buses and cars (Figure 13).

Figure 12. Anaerobic Digestion Process Overview
4.3.5 Summary Comparison of Biomass Direct Combustion and Gasification

Table 1 summarizes strengths and weaknesses of direct combustion and gasification. A key advantage of gasification over direct combustion is that gas combustion is potentially more efficient than direct combustion of the original fuel because it can be combusted at higher temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Combustion</strong></td>
<td>Proven, simple, lower-cost technology</td>
<td>Greater NOx, CO, and particulate emissions</td>
</tr>
<tr>
<td></td>
<td>Equipment is widely available, complete</td>
<td>Inefficient conversion process when generating power alone—some</td>
</tr>
<tr>
<td></td>
<td>with warranties</td>
<td>advanced designs are improving efficiency</td>
</tr>
<tr>
<td></td>
<td>Fuel flexibility in moisture and size</td>
<td>Requires water if generating power with a steam turbine</td>
</tr>
<tr>
<td></td>
<td>Lenders comfortable with technology</td>
<td></td>
</tr>
<tr>
<td><strong>Gasification</strong></td>
<td>Lower NOx, CO, and particulate emissions</td>
<td>Technology is in the development and demonstration phase</td>
</tr>
<tr>
<td></td>
<td>Potential for more efficient conversion</td>
<td>(close-coupled systems excluded)</td>
</tr>
<tr>
<td></td>
<td>process when generating power</td>
<td>Need fuel of uniform size and with low moisture content</td>
</tr>
<tr>
<td></td>
<td>Virtual elimination of water needs if</td>
<td>Generally requires clean-up of tar, water and other contamination</td>
</tr>
<tr>
<td></td>
<td>generating power without a steam turbine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(close-coupled systems excluded)</td>
<td></td>
</tr>
</tbody>
</table>

*Table 1. Comparative Strengths and Weaknesses of Biomass Direct Combustion and Gasification*
4.4 Municipal Solid Waste

A commonly accepted waste management hierarchy concludes that the first priority is to reduce the amount of waste, secondly it should be reused, and thirdly recycled. In the fourth place it becomes a resource that can be used to produce heat and electricity. Finally, waste that cannot be utilized for anything of the above should be landfilled. The European Union has announced its intention to phase-out biodegradable waste going to landfill in 2020-2025.

Countries with high utilization of waste combustion typically also have a well-functioning waste management system that follows the hierarchy mentioned above. Waste sorting typically improves the characteristics of the remaining waste material for energy generation.

It is important to assess the potential impact of future reductions in waste volume, due to further progress on waste recycling, on the long-term economics of energy generation from waste.

Burning waste as fuel has the advantage of not only replacing scarce fossil fuels but also greatly reducing the problem of waste disposal. Sweden converted their waste management from a societal burden to an environmentally oriented economic resource. As an economic driving force for the conversion, a fiscal fee was gradually imposed for landfilling. This resulted in a market-based revenue stream for the Waste-To-Energy (WTE) facility.

4.4.1 Waste to Energy Technologies

WTE is the process of producing electricity and/or heat from the combustion or other processing of waste materials, particularly municipal solid waste (MSW). Sometimes this is called Energy From Waste (EFW). Combustion is the most common WTE approach, although some processes use waste as a feedstock to produce a combustible fuel commodity, such as methane, methanol, ethanol or synthetic fuels.

Many WTE plants either combust MSW directly in a process called “mass burn” to generate electricity only, or both electricity and thermal energy, using a boiler and steam turbine technology. In an alternative approach called Refuse-Derived-Fuel (RDF), MSW is first processed to remove non-combustibles and to make the particle size more uniform. The RDF is then combusted, sometimes in a mixture with coal, to produce electricity and/or thermal energy using a boiler and steam turbine technology.

There are a number of other new and emerging technologies that are able to produce energy from waste and other fuels without direct combustion. Some of these technologies have the potential to produce more electric power from the same amount of fuel than would be possible by direct combustion. This is mainly due to the separation of corrosive components (ash) from the converted fuel, allowing higher combustion temperatures through conversion into liquid or gaseous fuels. These processes include:

- Gasification to produce combustible gas, hydrogen and synthetic fuels
- Pyrolysis to produce combustible tar/biodiesel and chars
- Thermal depolymerization to produce synthetic crude oil
• Plasma arc gasification to produce syngas and potentially usable products such as vitrified silicate, metal ingots, salt and sulphur
• Anaerobic digestion to produce biogas
• Fermentation to produce ethanol, lactic acid, and hydrogen

Burning MSW produces nitrogen oxides (NOx) and sulfur dioxide (SO2) as well as trace amounts of toxic pollutants such as mercury compounds and dioxins. Although MSW power plants do emit CO2, the biomass-derived portion is considered to be carbon neutral. The plants and trees that make up the paper, food, and other biogenic waste remove carbon dioxide from the air while they are growing, which is returned to the air when this material is burned. In contrast, when fossil fuels (or products derived from them such as plastics) are burned, they release CO2 that has not been part of the Earth's atmosphere for a very long time (i.e., within a human time scale).

4.4.2 Implementation of WTE

WTE is commonly practiced in Europe (for example, see case study from Östergötland, Sweden). In 2013, the city of Coventry in the UK began operating the first phase of a district heating scheme using heat from a waste incinerator (Figure 14). A 13 MWe municipal waste pyrolysis gasification plant initiated operations in Avonmouth UK in June 2013.

Few WTE facilities have been built in North America in recent decades, with proposals often constrained by Not In My Back Yard (NIMBY) sentiments. However, some additional energy recovery from existing WTE facilities is occurring. For example, after operating a mass burn WTE plant as a power-only power plant, Hennepin County is now also exporting steam to the downtown Minneapolis steam district heating system. The County is also exploring the potential for new hot water district heating infrastructure to utilize more of the thermal output of the facility.
4.5 Geothermal Heating

Heat energy continuously flows from the Earth’s interior to the surface, as illustrated in Figure 15. The resulting heat is not distributed uniformly over the Earth’s surface but is concentrated along active tectonic plate boundaries where volcanic activity has transported high temperature molten material nearer to the surface. Under the right conditions, water penetrates deeply into the surrounding hot rock zones, resulting in the formation of high temperature geothermal systems containing hot water and/or pressurized steam. In addition, groundwater naturally circulating through deep fracture zones can collect heat from large volumes of rock and concentrate it in shallow reservoirs, even if far away from plate boundaries. In some cases, the water is discharged as hot springs. This hot water is typically at a lower temperature than when produced in deeper volcanic-based systems. Where high temperatures exist, the heat can be used in conventional technology for electricity generation or for direct heat use applications.
Depending on the temperature of the geothermal resources and the technologies used, geothermal heat can be used to produce electricity and/or thermal energy. High temperature geothermal resources can be used to generate power with steam turbine generation technology. Medium and low temperature geothermal resources can be used for heating by transferring heat through heat exchangers. Medium to low temperature geothermal sources can also be used to generate electricity with Organic Rankine Cycle (ORC) technology. As discussed above under Bioenergy, ORC uses hot water to heat a working fluid that has a lower boiling point than water (such as pentane or other volatile organic compound). In this manner, electricity can be produced from low-temperature (approximately 85°C and greater), low-pressure resources. Húsavík Energy on Iceland operates with a technique called Kalina, which uses a water/ammonia mixture instead of pentane (see case study).

4.6 Solar Thermal

Solar thermal systems convert solar radiation into heat with a wide range of technologies. Solar thermal systems produce heat directly, and some technology configurations produce cooling via heat-driven chillers.

4.6.1 Flat Plate Solar Collectors

In this solar thermal technology, water or another heat transfer fluid is circulated through a duct and is heated by transfer from direct solar radiation on the collector panel (Figure 16). Although there are a wide variety of designs, flat plate collectors generally produce hot water at temperatures under 95°C (200°F) for efficiency reasons.

Collector efficiency increases with a decrease in the temperature difference between the collector fluid temperature and the ambient temperature. This is illustrated in Figure 17 for different models of collectors offered by Arcon, a Danish manufacturer. 14
Figure 16. Flat Plate Solar Thermal Collectors

Figure 17. Efficiency of Flat Plate Solar Collectors
4.6.2 Evacuated Tube Solar Collectors

Evacuated Tube Collectors (ETCs) are made in many different ways, but all of them use vacuum to insulate the absorber. An example of an ETC unit is shown in Figure 18. In ETCs the heat can either be gathered by means of a solar collector fluid flowing through the absorber (as in flat plate collectors) or it can be collected by means of the heat pipe principle. In a heat pipe there is only a small amount of fluid sealed inside each evacuated tube. The energy transfer takes place in four steps:

1. This fluid is evaporated by the solar radiation.
2. The vapor rises to the top where it meets a (colder) pipe where a liquid flows through.
3. The vapor is condensed, thus transferring the latent heat to the liquid in the top pipe.
4. The condensed fluid in the evacuated tubes runs back to the bottom of the tube where the process can start again.

ETCs more efficiently produce higher temperatures compared with flat plate collectors, as illustrated in Figure 19.
4.6.3 Concentrating Solar Collectors

These devices use a variety of designs to concentrate solar radiation in order to achieve higher temperatures. The concentrator captures solar radiation and directs it to the receiver where the heat energy is absorbed by a fluid – normally a special type of oil. The hot fluid is then transported in a pipe to enable the heat to be used directly via a heat exchanger or stored for later use at night or during less-sunny days. A popular design consists of parabolic troughs in long arrays of identical concentrating modules, resembling trough shaped glass mirrors that track the sun daily from east to west (Figure 20). They concentrate the solar radiation onto the absorber pipe located in the focal line of the installation.
One area of growing interest is solar-assisted cooling for air-conditioning and refrigeration. This interest is driven by the fact that peak cooling demands often correlate with peak solar radiation and hence with peak electricity loads for conventional air conditioners. These thermally driven processes are more complex, and are based on a thermo-chemical sorption process. A liquid or gas can either be attached to a solid, porous material (adsorption) or absorbed by another liquid or solid material (absorption). Closed systems including both adsorption and absorption chillers can be used to produce chilled water for air conditioning. Open cooling cycles use desiccant and evaporative cooling systems that directly condition air. The technology has not been widely applied and needs more research, development and demonstration to increase reliability and reduce costs before it can compete with conventional cooling technologies.

4.7 Wind

A wind turbine is a device that converts kinetic energy from the wind into mechanical energy. If the mechanical energy is used to produce electricity, the device is called wind turbine or wind power plant.

Wind energy produces electricity or mechanical energy (e.g. for pumping). Although not economically feasible generally, the use of wind-generated electricity to produce hot water is implemented in some European district heating systems as a strategy (and revenue stream) for balancing power grids as a result of grid imbalances caused by wind, an inherently intermittent resource. Hot water can be stored if there is not an immediate use for this energy (see case study from Skagen, Denmark).

Wind turbines are manufactured in a wide range of vertical and horizontal axis types. Large grid-connected arrays of turbines are becoming an increasingly important source of wind power-produced commercial electricity.
4.8 Deep Water Cooling

Deep water cooling is a technology that uses cold water drawn from deep sources such as lakes or seas to provide cooling needs to buildings connected to a DES. Deep water cooling is a naturally renewable, sustainable energy system. The enormous reduction in electric power requirements for cooling yields commensurate reductions in greenhouse and ozone-depleting gases. Also, direct deep water cooling does not require any refrigerant-like chillers, so there is no chance of leakage of ozone-depleting refrigerant to the environment.

On the other hand, installation of deep water cooling systems can be potentially disruptive to the environment, and thermal impacts during operation must be carefully studied to ensure that aquatic ecosystems are not harmed.

4.8.1 Technology Configurations

A typical deep water cooling system includes the following components:

- An intake pipeline running from deeper parts of the water source to the shore.
- A heat exchange facility at the shore that isolates the open lake or sea water loop from the closed distribution loop that carried chilled water to customer buildings. This facility consists of heat exchangers, pumps, valves and controls, piping, and a structure to house it.
- An outfall pipeline that returns water to the water source at a shallow depth after it has passed through the heat exchangers on shore.
- A closed loop distribution pipeline (supply and return piping) that carries district cooling water from the heat exchange facility to the location of cooling loads and then back to the heat exchange facility.

Often, the temperature of the chilled water distribution supply in this closed loop is reduced further with electric chillers at times of peak cooling use. In most cases, deep water cooling systems return all of the water back to the source after cooling energy is extracted. Water is returned to the water source at shallow depths, where the water is warmer, to lessen or eliminate the impact of warm water rejection on the local ecosystem.

In addition to deep water cooling systems that use the water from the deep source to provide cooling “directly” to buildings, there are also some deep water cooling systems that use deep water as condenser water for chillers at a central cooling plant. The temperature of the condenser water from the deep water source is lower than that of condenser water cooled with a traditional cooling tower solution, which results in increased chiller efficiency and lower energy consumption. This type of system may be employed when deep water temperatures are not low enough for direct cooling use. Also, in systems with a combination of direct deep water cooling and electric chillers, deep source water can be used for both direct cooling and as condenser water for the chillers. In addition to energy savings, using a deep water source for condenser water heat rejection eliminates the need for cooling towers and the space and make-up water requirements they require.
4.8.2 Implementation

There are a number of district cooling systems utilizing deep water cooling throughout the world, particularly in Sweden. There are at least 7 deep water cooling systems in Sweden. Examples include:

- Stockholm, where the Baltic Sea is used in combination with heat pumps to supply over 70 MW (20,000 tons of refrigeration or TR) for downtown Stockholm (see case study).
- Södertälje, with a 60 MW (17,000 TR) district cooling system at Lake Mälaren supplying a pharmaceutical plant and other commercial customers.
- Sollentuna, a 4 MW (1,100 TR) district cooling system that includes aquifer storage. During the winter, cold sea water from a bay of the Baltic Sea is stored in the aquifer to reduce the warmer temperature of the sea water during summer.

Figure 21 shows polyethylene pipe being installed in Lake Mälaren.

Figure 21. Pipe Installation in Lake Mälaren, Sweden

A deep lake water cooling system has been implemented to provide cooling for the Cornell University campus. In Toronto, the largest lake water cooling system in the world uses Lake Ontario as its water source. The Toronto deep water cooling is designed to use part or all of the water drawn from the water source as potable water after the cooling energy has been extracted from it (see case study).

4.8.3 Efficiency

Deep water cooling is extremely efficient. For systems without peaking chillers, the only energy costs are those required for pumping the water-source and transmission pipelines. As an example, since startup, the Cornell deep lake cooling system has been operating with an annual average energy consumption of 0.10 kWh/ton-hr.\textsuperscript{15}
4.8.4 Economic Factors
Deep water cooling systems are always capital intensive, but the capital cost required for these projects can vary significantly from one project to another. Some of the most important factors that can affect the capital cost are:

- Distance from the shore of the water source to the location of the cooling load.
- Length and depth of the intake pipeline required.
- Amount, if any, of chiller capacity that must be installed to supplement deep water temperatures.

One benefit of deep water cooling with respect to capital cost is that system life for a deep water cooling system may be expected to be 2-3 times as long as for mechanical chillers.

Operating costs will be incurred for maintenance of the intake structure, intake and outfall pipelines, the transmission pipeline, pumps and heat exchangers that separate the two loops. The intake and outfall pipelines may require regular pigging to clean out growth of algae or crustaceans within the pipelines.

There are both positive and negative aspects to siting and infrastructure issues surrounding deep water cooling. On the positive side, a deep water cooling system significantly reduces the footprint required for a cooling plant site compared to a straight centrifugal or absorption chiller plant. In addition to plant cost reduction, this may allow for more creative siting of a cooling plant. Another benefit of deep water cooling is that it eliminates the need for cooling towers at the plant. The elimination of the need for rooftop space for cooling towers and the absence of a cooling tower plume can make plant siting much more flexible and affordable.

4.8.5 Reliability
Deep water cooling systems have the potential to be very reliable sources of cooling. Although no statistics were obtainable for this study, anecdotal evidence suggests that the existing systems have operated very reliably. Because a single pipeline carries cooling from the deep water source, this lack of redundancy may prove a serious concern to some potential customers, particularly customers like research facilities for whom reliability is critical.

Reliability concerns are alleviated, to a certain extent, if the deep water cooling system is supplemented with electric chillers at the central plants in order to bring the chilled water temperature down sufficiently at times of peak cooling demand. This allows a portion of the peak system load to be served even if a problem arises with the deep water cooling transmission pipeline, intake pipeline, or outflow pipeline.

4.9 Heat Pump Technologies
Heat pumps are devices that move heat from a heat source at a lower temperature to a heat sink at a higher temperature (see section 7.2.7 for a discussion of temperature compatibility). Heat pumps effectively reverse the natural process of heat flowing from a higher temperature substance to a lower temperature substance. Typically, this is accomplished with a mechanical device such as a compressor, usually powered with electricity. A heat pump is like a chiller or
other refrigeration device, using the conventional vapor-compression refrigeration cycle, except that to produce heat:

- The heat source is one of a number of water or air sources, instead of the district cooling or building cooling loop; and
- Instead of rejecting heat to the environment through the condenser water loop, the heat is provided to the district hot water supply or the building space.

Heat pumps can be used to provide:

- heating only;
- heating or cooling; or
- heating and cooling simultaneously.

The seasonal coefficient of performance (SCOP) is the ratio of heat (or cooling) output to energy input. Heat pump efficiencies are strongly affected by the temperature lift, as illustrated in Figure 22. Temperature lift should be minimized to obtain highest efficiency. The output temperature of a heat pump depends on the source temperature and the particular heat pump design, including whether units are connected in series. Generally, the maximum practical output temperature of a heat pump is approximately 80°C (175°F).

![Figure 22. Heat Pump COP vs. Temperature Lift](image-url)
Heat pumps do not have any direct air pollution impacts, although they would have indirect emissions impacts to the extent that the electricity used to meet the heat pump requirements was generated with fossil-fuel-based power plants. For example, if electricity is from a power plant burning fuel at, say, 33%, then a COP of about 3 will achieve a life cycle efficiency of 90% to 100% (slightly higher than a natural gas boiler). It is also important to consider the fuel for the electricity; if it is coal, then the GHG implications are negative (compared with a gas boiler). As electricity grids decarbonize, the attractiveness of heat pumps from a GHG perspective will increase. Heat pumps would also have some impact on stratospheric ozone depletion due to leakage of refrigerant.

The role of heat pumps in the DES sector has evolved over the years. For example, significant implementation of heat pumps using seawater, lake water or sewage effluent occurred in Sweden in the 1980s with the availability of surplus electricity capacity from nuclear plants. During this period a number of large heat pumps, up to 55 MegaWatts (MW) thermal (about 188 million Btu/hour), were installed. In the 1990’s some of the heat pumps were adapted to simultaneously supply district heating from the heat pump condenser and district cooling from the heat pump evaporator for those times of the year (spring, fall and winter) when both heating and cooling are required.

However, by the end of the 1990s, with the de-regulation of the electricity market, Swedish electricity prices began to rise. Due to power these price changes, and other drivers, some base load heat pumps plants were replaced with biomass boilers or municipal waste incineration in larger DES systems. However, in DES systems supplying both cooling and heat, large scale heat pumps are still competitive.

In recent years, heat pumps in the multifamily residential and commercial sectors (the latter mostly in combination with space cooling) have created increased competition for DES. This trend was driven by the gradual de-regulation of local heating markets, which has brought new actors, diversity in products and changes in equipment pricing.

4.9.1 Geo-Exchange

Geo-exchange is not properly considered an energy source but rather is the use of naturally occurring shallow earth temperatures to increase the efficiency of using electricity to produce heating or cooling using heat pumps.

For example, water can be pumped from a well, circulated through the heat pump and injected into a second well or pumped to a surface water body. Alternatively, surface water (sea water or lake water) can be used as a heat source and/or sink. Ground Source Heat Pumps (GSHP) systems are closed loop systems using vertical boreholes or horizontal trenches to circulate water through the ground to heat or cool it (Figure 23).
Conventional GSHP systems are usually considered to have a seasonal coefficient of performance for heating ($\text{SCOP}_h$) of 3 to 4. Proper design, installation, operation and maintenance are essential to achieving design SCOPs. Although data are usually lacking to document the gap between design SCOP and actual SCOP, it is notable that test results for small (domestic) ground source heat pumps in the United Kingdom (UK) indicate significantly lower efficiencies (Figure 24) than the anticipated level of $>3.0$. The weighted average heating $\text{SCOP}_h$ for 83 domestic ground source heat pumps in the UK study was 2.34. These results may well reflect poor design, installation, operation and maintenance – which are generally far superior in district energy system compared with a typical domestic heat pump installation.
Ball State University has the largest district heating and cooling ground-sourced geothermal facility in the U.S (see case study).\textsuperscript{17} Completion of the first phase in Nov. 2011 has allowed the university to shut down two of its four coal-fired boilers, cutting carbon emissions in half. The system will connect nearly 3,600 boreholes, 150 m (500 ft) narrow vertical wells with loops of pipes surrounded by grout. The boreholes cover 0.1 – 0.15 km\textsuperscript{2} (25 to 40 acres), buried under an old soccer field, parking lots and other green fields. Eventually, the system will bring heat and air conditioning to more than 500,000 m\textsuperscript{2} (5.5 million square feet) in 47 buildings.

In addition to conventional GSHP, there are also experimental direct-expansion ground source heat pumps (DX GSHP) that use a working fluid other than water that can be evaporated directly in the ground coils. A DX GSHP uses a buried copper piping network through which refrigerant is circulated. Compared with the conventional GSHP, the DX GSHP system is more efficient, with lower thermal resistance in the ground heat exchanger and a lower (higher) condensing (evaporating) temperature in the cooling (heating) mode.\textsuperscript{18}

The efficiency and reliability of DX GSHP is higher compared with conventional heat pumps because there is no need for an intermediate heat exchanger. A case study in China shows that compared with conventional ground source heat pumps the DX GSHP has higher initial costs, but lower operating costs and less greenhouse gas emissions.\textsuperscript{19}
4.9.2 Chiller Heat Recovery

For typical water-cooled chiller equipment, nearly 80% of the energy in the condenser water is heat transferred from the chilled water loop. The other 20% is energy that is generated by the work done by the compressor in order to produce the refrigeration cycle. Typically, all of this energy is rejected though cooling towers into the atmosphere.

Chiller heat recovery is a unique “resource” because heat is produced in the process of air conditioning, thus providing an opportunity to “kill two birds with one stone.” The heat extracted from building space that is normally exhausted to the atmosphere through cooling towers can be recovered and used in a low-temperature hot water district heating loop. A heat recovery chiller (HRC) is designed to be able to more efficiently use the energy that is normally rejected though the cooling towers.

Stanford University is now replacing its steam system with hot water as part of a long-term plan to integrate the heating system with the district cooling system, recovering rejected chiller heat for a low-temperature district heating system (see case study). Figure 25 show an example daily load profile from Stanford, illustrating the overlap of heating and cooling loads. Hot water and chilled water storage can help optimize use of recovered heat.

Ground source heat pumps are being considered to enhance the scheme. Figure 26 shows the design temperatures for the HRC system, with potential integration of ground source heat pumps, at Stanford University. Further information can be found in the case study.

Figure 25. Illustrative Daily Heating and Cooling Load Profile
4.9.3 Sewage Heat Recovery

As noted above, heat recovery from sewage effluent has been implemented in Europe for decades. There is growing interest in North America in recovering heat from sewage effluent or even untreated sewage. The South East False Creek Energy Centre in Vancouver, British Columbia, recovers heat from sewage to provide the base heat load for a development that includes the Olympic Village, home of the recent 2010 Winter Olympics (see case study). A schematic illustration of the system is shown in Figure 27. The heat pumps work by pumping filtered but otherwise untreated warm sewage 20±2°C (68±3.6°F) through the evaporator side of the heat pump. This heat, coupled with the mechanical compression of the refrigerant, produces 65 - 82°C (149 - 180°F) hot water on the condenser side of the heat pump.

The weighted average seasonal heating SCOPₜ for the sewage heat recovery system in False Creek has so far been 3.3.
4.10 Industrial Waste Heat Recovery

Industrial waste heat is heat generated as a byproduct of industrial processes. Worldwide the potential of industrial waste heat is huge, but the actual heat recovery in district energy systems is still very small. Industrial waste heat may come from a fossil origin but would still be considered as a good application because it productively uses what would otherwise be wasted heat.

Financially and contractually, the biggest challenge with industrial heat recovery achieving sufficient confidence that the industrial plant will stay in operation long enough to pay off the capital cost of installation of heat exchangers and thermal distribution systems required to recover and transport the heat. It is also important to ensure that there is ready access to the industrial plant for maintenance of heat exchangers and other equipment.

The district heating system of Lindesberg, Sweden, receives 85% of its energy from a cardboard mill (Korsnäs Frövi). The waste heat source is limited in temperature to 86°C (187°F) but available over the full year (see case study). The district heating system in Skagen, Denmark receives waste heat from a producer of fish meal and fish oil (see case study).

4.11 Flue Gas Heat Recovery

Flue gas heat recovery (FGHR) is a process in which flue gas is cooled below its dew point and the heat released by the resulting condensation of water is recovered as low temperature heat. This increases efficiency by capturing the latent heat of vaporization (Figure 28), thereby reducing fuel use when systems actually deliver the return water temperature required to
enable condensation of water vapor from flue gas. Cooling of the flue gas can be performed either with a heat exchanger or via a condensing scrubber (Figure 29).

The heat recovery potential of FGHR is highest for fuels with a high moisture content (e.g. biomass), and where heat is useful at the lowest possible temperatures. In Europe, FGHR is normally implemented at biomass fired boilers and waste incinerators supplying district heating systems with relatively low return temperatures (below about 55°C or 130°F).

In combination with a low temperature hot water system, FGHR can save energy in a biomass plant burning wet fuel. The main cause for the reduced boiler efficiency is latent heat loss from moisture and hydrogen combustion due to the wet biomass.

![Figure 28. Efficiency Improvement from Flue Gas Condensation (Example)](image-url)
Figure 29. Condensing Flue Gas Heat Recovery Unit
5 Fundamental Considerations for Integrating REWH

5.1 Introduction
There are several key technical and business considerations which must be addressed when evaluating integration of REWH into a DES. Some of these considerations are specific to the particular REWH, as discussed in section 7.2. In this section, we address fundamental characteristics that affect the integration of REWH into a new or existing DES.

5.2 Technical Considerations
The fundamental technical considerations fall into two categories:

- Temperature – at what temperature is the REWH available, and how does it compare with the supply and return temperatures of the DES?
- Availability – how reliably and when is the REWH available compared with the DES energy requirements on an hourly and season basis?

For any given REWH resource the above design fundamentals have to be evaluated and optimized in the context of economic and environmental trade-offs.

5.2.1 Impact of Temperature
A pervasive issue relative to tapping renewable and waste heat sources is the temperature of the resource compared with the supply and return temperatures of the DES network. With lower district heating (DH) operating temperatures a greater range of REWH sources becomes available. Figure 30 shows representative temperatures for a range of example REWH resources. This figure is not exact and certainly exceptions exist but it gives the reader a quantitative illustration of the characteristics of these resources.

Given the multiplicity of industrial waste heat sources, only two examples are given for simplicity of presentation. A broad band of geothermal hot water temperatures is shown because such resources can vary significantly from one site to another. The thermal efficiency of reciprocating engine CHP is increased if the DH temperatures are low enough to recover heat from jacket water and lubricating oil as well as the relatively high-temperature exhaust gas. Lower DH temperatures make it possible to produce useful heat with lower-cost flat-plate solar collectors in comparison with higher-cost evacuated tube collectors. (The efficiency of evacuated tube collectors in generating higher temperatures is substantially better than that of flat plate collectors.)

For thermal sources that require a heat pump, the temperature boost from the heat pump is shown in grey and is added to the source itself. The efficiency of these technologies is significantly affected by the required temperature lift, which should always be kept to the minimum required for highest efficiency. While some consider heat pump schemes to represent renewable energy, the reality is that sources such as groundwater or sewage effluent are a means of increasing the efficiency with which electricity is converted to thermal energy.
Unless and until electricity grids are decarbonized, such heat pumps systems cannot truly be considered renewable.

**Figure 30. Representative Temperatures of Selected REWH Resources**

REWH resource temperatures must be compared to the supply and return temperatures of district heating distribution systems. In North America many district heating systems distribute steam. Distribution pressures vary, generally in the range of 1.4 barg (20 psig) to 13.8 barg (200 psig). Some systems operate at pressures at higher than 13.8 barg, and some distribute superheated steam. Many systems operate both low and high pressure systems. The temperatures of typical high and low pressure (saturated) steam systems are illustrated in Figure 31.
There is a strong trend toward reducing district hot water supply and return temperatures. The evolution of district heating has been characterized in terms of “generations” with the first being steam, the second being hot water systems supplying (at peak conditions) >100°C (212°F), the third being hot water systems supplying 80-100°C (176-212°F), and the fourth being systems supplying less than 65-75°C (149-167°F). These are not exact categories, and standard approaches differ from country to country. As district heating temperatures are reduced, the major concern is with the potential for legionella in the DHW, particularly during summer operations.

In this report we will use a somewhat different nomenclature than the categories outlined above regarding the four “generations” in order to better encompass North America systems. Table 2 summarizes peak supply temperatures (and steam pressures, as appropriate) for five DH system types. The three representative hot water systems are illustrated in Figure 31, indicating peak supply temperatures as well as typical return temperatures.
One critically important factor when considering the temperature scheme is understanding of temperature duration and the fact that peak supply temperatures in most systems only have to occur for a few hundred hours per year. Hot water systems are usually designed to reduce temperatures during off-peak times, thereby further facilitating use of REWH.

In order to reduce distribution system capital costs to an optimal level, low temperature systems will likely be designed to boost supply temperatures for the few annual hours when the highest loads are experienced. In the graph we generalize the peak supply and return temperatures of these low temperature systems as 70/35°C (167/95°F).

Resources can be separated into the following groups depending on the specific annual temperatures of the resource:

- **High Grade** sources have reliably high temperatures that always exceed the DES supply temperature. These sources can be used directly whenever available.
- **Low Grade** sources have temperatures that are sometimes or always insufficient relative to the DES supply temperature but always sufficient relative to the DES return temperature. If the temperature of the source falls below the DES supply temperature, the temperature must be polished (increased for heating or decreased for cooling) with other energy sources.
- **Below Grade** sources always have temperatures lower than the return temperature in the DES. These sources must be upgraded with a heat pump.

As long as the temperature of the REWH is higher than the return temperature in the DES (heating mode, opposite for cooling) the resource can be used directly. When the temperature is lower than the return temperature in the DES (heating mode, opposite for cooling), either the temperature must be upgraded with a heat pump or the existing DES (or the design of a new DES) must be modified in order to use the REWH. In considering temperatures it is also important to note that a further temperature differential between the resource and DES temperature generally is required due to the use of heat exchangers.

When the temperature of the REWH is lower than the return temperature in the DES (heating mode, opposite for cooling), an existing DES could adapt in a number of ways, e.g.:

---

**Table 2. Representative Supply and Return Temperatures (Peak Condition) for Five Types of District Heating Systems**

<table>
<thead>
<tr>
<th></th>
<th>Peak Supply Temperature</th>
<th>Steam Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>F</td>
</tr>
<tr>
<td><strong>Steam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High pressure</td>
<td>194</td>
<td>381</td>
</tr>
<tr>
<td>Low pressure</td>
<td>126</td>
<td>259</td>
</tr>
<tr>
<td><strong>Hot water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature</td>
<td>120</td>
<td>248</td>
</tr>
<tr>
<td>Medium temperature</td>
<td>100</td>
<td>212</td>
</tr>
<tr>
<td>Low temperature</td>
<td>70</td>
<td>158</td>
</tr>
</tbody>
</table>

---

1. Make improvements to achieve low return temperature. Typically this could include minimizing bypasses in the system and/or improving process control and coil performance at customer buildings. Such measures have costs, and could be funded either directly by the DES utility (if determined to be cost-effective on a life cycle basis in comparison with other options) or indirectly by encouraging customer investments to improve delta T (see “Business Considerations” below).

2. Curtail the flow or the temperature to achieve low return temperature. This approach requires careful consideration and testing before implementation to ensure continued customer comfort.

3. Find other low grade heat sinks to further reduce the return temperature such as usage of the return water for preheating, snow melting etc.

If adaptation is not possible or insufficient, the use of REWH can be enabled by replacing the high temperature district heating system (often a steam system) with a lower temperature system.

One of the key benefits of hot water DH is the ability to set back system temperatures throughout the year, which facilitates integration of REWH (Figure 32). The temperature scheme should be optimized based on the available energy resources. Keeping a low supply temperature throughout the year can facilitate direct use of a REWH without the need to polish with a conventional source. For existing systems (not designed for low temperatures) low supply temperature has to be carefully integrated to ensure customer comfort at all times.

Low district heating temperatures also minimize distribution heat losses, but there may be an economic trade-off since reduced temperatures normally increase costs for building systems and could potentially reduce the delta T in an existing system (not designed for low temperatures), with additional flow requirements as a result.
Figure 32. Examples of Hot Water Temperature Schemes as a Function of Outdoor Air Temperature

Keeping a relatively high supply temperature throughout the year should in theory result in a lower return for any given system, which could facilitate additional use of a REWH and reduce costs for hot water distribution and building systems. In practice however many systems will see the return temperature rise with the supply due to poor process control and/or bypasses between supply and return. There is also an economic trade-off with respect to higher heat loss in the distribution system.

As previously noted, peak supply temperatures in most systems only have to occur for a few hundred hours per year. This is illustrated in Figure 33 for the three hot water representative DH temperature schemes used in this report. As district heating temperatures are reduced, the major concern is with the potential for legionella in the DHW, particularly during summer operations.
Table 3 summarizes generalized peak, summer setback and annual weighted average temperatures for three hot water temperature regimes. It is the weighted average temperature that is an important criterion for efficiency and economic comparison of heat source options. The average temperature performance for 140 current Swedish district heating systems, as illustrated in Figure 34, is in between the medium and low temperature regimes shown in Table 3.

### Table 3. Representative Peak, Setback and Annual Average Temperatures for High, Medium and Low Regimes

<table>
<thead>
<tr>
<th>Temptures in Celsius</th>
<th>Peak Supply</th>
<th>Peak Return</th>
<th>Setback low Supply</th>
<th>Setback low Return</th>
<th>Annual average Supply</th>
<th>Annual average Return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120</td>
<td>70</td>
<td>80</td>
<td>55</td>
<td>98</td>
<td>62</td>
</tr>
<tr>
<td>High temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium temperature</td>
<td>100</td>
<td>55</td>
<td>70</td>
<td>45</td>
<td>84</td>
<td>50</td>
</tr>
<tr>
<td>Low temperature</td>
<td>70</td>
<td>35</td>
<td>55</td>
<td>30</td>
<td>62</td>
<td>32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tempers in Farenheit</th>
<th>Peak Supply</th>
<th>Peak Return</th>
<th>Setback low Supply</th>
<th>Setback low Return</th>
<th>Annual average Supply</th>
<th>Annual average Return</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>248</td>
<td>158</td>
<td>176</td>
<td>131</td>
<td>208</td>
<td>143</td>
</tr>
<tr>
<td>High temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium temperature</td>
<td>212</td>
<td>131</td>
<td>158</td>
<td>113</td>
<td>182</td>
<td>121</td>
</tr>
<tr>
<td>Low temperature</td>
<td>158</td>
<td>95</td>
<td>131</td>
<td>86</td>
<td>143</td>
<td>90</td>
</tr>
</tbody>
</table>
Figure 34. Annual Average Supply and Return Temperatures for 140 Swedish District Heating Systems

In Figure 35 through Figure 39, the illustrative annual average district heating temperature regimes are superimposed on the REWH resource temperatures, highlighting impact of system temperatures on REWH utilization. For example:

- High pressure steam systems are limited to combustion of renewable fuels (not shown in these figures), or high-temperature industrial waste heat or high-temperature geothermal hot water or steam (Figure 35).
- Low-pressure steam systems have the potential to pick up a broader array of industrial waste heat or geothermal heat, and can also utilize heat from reciprocating engine jacket water (Figure 36).
- High temperature hot water systems have the additional potential to recover heat from flue gas condensation as well as a range of low-temperature resources aided by heat (Figure 37).
- Medium temperature hot water systems are able to recover heat from flue gas condensation as well as a range of low-temperature resources aided by heat pumps (Figure 38).

Low temperature hot water systems (Figure 39) can increase recovery of heat from low temperature resources, and allow for more efficient production of heat via heat pumps due to a lower temperature lift (as illustrated in Figure 22).
While lower-temperature district heating systems expand the opportunities to tap REWH resources, a variety of other factors must be addressed to obtain an optimal result relative to efficiency and economy, as discussed in the next section of this report.

*Figure 35. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of High Pressure Steam*
Figure 36. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of Low Pressure Steam

Figure 37. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of High Temperature Hot Water
Figure 38. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of Medium Temperature Hot Water

Figure 39. Representative Resource Temperatures Compared with Annual Average Supply/Return Temperature Range of Low Temperature Hot Water
5.2.2 Impact of Load Availability

Another critical aspect of a REWH is its availability on an hourly or seasonal basis. Some resources, such as solar and wind, are intermittent and therefore are not dispatchable. Further, the seasonal distribution of the resource may be counter to the seasonal distribution of the thermal requirement. The hourly availability of resources such as industrial waste heat is tied to the operating hours of the industrial facility, and may be subject to interruptions.

With a thorough understanding of availability, the capacity of the REWH can be properly sized. Typically, renewable energy sources have lower operating cost but have higher capital costs and lower turndown capability (although some exceptions exist, such as bioliquids). It is therefore of utmost importance to find the optimal sizing, given the size and load duration for the DES, to provide the best life-cycle cost and stable pricing well into the future.

A DES load-duration curve (LDC) indicates, on an annual basis, the time that the load requirement is greater than a given value in a typical year. LDCs are useful tools for visualizing the load profile throughout the year; they show, among other things, that peak demand only occurs for a very short time. In the example LDC shown in Figure 40, the system load demand is expected to be greater than 67% of the peak for only about 300 hours per year at full build-out. The shape of the LDC will vary based on climate and the characteristics of the customer base.

![Figure 40. Example of Load Duration Curve (LDC) for a DES](image)
LDCs also assist with sizing heat source options and estimating the energy that each source would contribute on an annual basis. Annual energy is equal to the area under the curve. Figure 40 shows that a renewable energy source with a higher capital cost but a lower operating cost sized for 33% of the peak capacity will supply 75% of the annual energy for the system (Heat source 1). The remaining energy could be provided by an energy source with lower capital cost and a higher fuel cost as it is used very little and is required for backup in any event. Heat source 3 in Figure 40 supplies only 2% of the annual energy.

A competitive energy production has to be based on the optimal balance between capital investment, risk mitigation and operating costs, viewed within the context of the LDC. The optimal scheme will vary for different locations and customer mixes (see further discussion in section 6).

Sizing a REWH source that is intermittent and/or interruptible requires careful optimization. One option is to undersize the REWH source and continuously polish with a conventional energy source. Integration of the REWH source with thermal energy storage offers greater flexibility. The type of thermal storage depends on the availability pattern of the resources, and may be daily or seasonal storage. For example, Figure 41 shows the same LDC graph as Figure 40 but now with a seasonal storage. As can be seen in the figure heat source 1 can now run full load the whole year (charging the storage between 4,400 – 8,760 hours and discharge between 0 – 4,400 hours). There is potentially no longer a need for heat source 2.

Depending on the availability pattern and economics of the REWH, it may be advisable to oversize the REWH source and convert it for some other purpose or throw it away. Obviously this option doesn’t sound very productive but there may be situations where there may be seasonal benefits, and the additional capital costs can be justified to oversize the REWH source.
5.3 Business Considerations

5.3.1 Fundamental Drivers
There are three fundamental drivers for any change to an existing DES:

- Load growth.
- System optimization and cost reduction.
- Reduction in environmental emissions.

Increased customer load may require additional production capacity, providing an opportunity to integrate REWH. Alternatively, a REWH may offer the potential to reduce life cycle costs compared to current energy sources. Although rarely the key driver, goals for reduction in GHG or other emissions may also affect the decisions on modification of existing systems. In some markets there are policies providing significant incentives for reducing fossil fuel use and increasing use of REWH, such as grants/rebates, taxes, production support and/or market oriented systems such as emission allowances or quota obligations. There are also some customers that are willing to pay a premium for “green” energy.

Urban planning and building regulations can be an important driver for encouraging buildings to connect to a DES using REWH.
Financing a REWH project can be challenging because future energy prices are uncertain. This includes the likelihood that waste heat or other resources that are currently free or very low cost may become more expensive in the future. In assessing options it is useful to consider the benefits of a given change relative to the flexibility to respond to new technical opportunities or changing price conditions.

5.3.2 Production Considerations

When implementing a new production source into a DES, it is of utmost importance to develop a policy and operational strategy for right of precedence for energy delivery into the district scheme.

Distribution of district energy is a “natural monopoly” whilst production of district energy is not necessarily a natural monopoly. This is because the required investments in distribution infrastructure are very large. Therefore, it is economically inefficient to have two distribution networks parallel to one another.

In some countries Third Party Access (TPA) policies require owners of natural monopoly infrastructure facilities to grant access to those facilities to parties other than their own customers, usually competitors in the provision of the relevant services, on commercial terms comparable to those that would apply in a competitive market.

TPA can be a step toward a conceptually attractive vision of district energy systems as community energy brokers, in which the DES would purchase, transport and re-sell thermal energy. Realizing such a vision would promote sustainability by reducing fossil fuel consumption.

However, there may be conflicts between those wanting to put energy into the distribution system and both the central producer and other (possibly competing) inputs of renewable energy or waste heat. For example, high wind turbine output causes CHP plants to shut down in Denmark and thus the efficiency gains of CHP are lost. A central CHP plant may lose heat load if local solar or waste heat recovery increases.

Other important aspects/foundations for sustainable REWH DES are confidence in the actual business concept between the DES system owner and producers, as well as transparency in the financial reporting.

5.3.3 Customer Considerations

The customer contract is the most important document for communication between the DES system operator and its customers because it can influence the performance of the building system in ways that can help or hinder the total efficiency and cost-effectiveness of the DES. This becomes even more critical with medium or low temperature district heating systems.

One significant barrier to integrating REWH systems into existing schemes relates to contractual obligations to customers with regard to supply temperatures. These are often long term (20-40 year) agreements and will typically stipulate particular minimum (for heating) or maximum (for cooling) supply temperatures. These temperatures are often set to satisfy existing equipment but also are subsequently used to design new systems within a building (including DHW systems). This clearly needs to be considered early on in any contractual
discussions and this flexibility should be built into agreements to enable variable flow temperatures, probably subject to certain minimum requirements at different times of year.

Customer contracts should have penalties or other means of enforcing delta T performance by customers. Contracts could include, for example, an excess flow for additional flow beyond a threshold established per unit of delivered thermal energy based on targetted delta T. Just a small number of existing, poorly controlled customer buildings connected to a district heating scheme, requiring higher supply temperatures due to historic plant, can determine the operating regime for the whole scheme.

In addition to the benefits to the DES, modifications to building systems to increase delta T can provide indirect benefits to the end user through reduced secondary system heat losses and lower electricity consumption (with variable speed pumps). Assessment of customer building delta T improvements requires a careful cost-benefit analysis.

It is important to incorporate economically transparent price signals in the customer tariffs. Dependent on philosophies, the pricing can either be based on costs or market principles. Price signals in the contract can influence technical performance, for example by encouraging high delta T and discouraging low delta T, thereby reducing distribution losses and improving energy conversion in the plants. Price signals can also influence customer management of peak demand in district cooling systems by, for example, “pre-cooling” buildings before occupancy to reduce morning start-up peak in district cooling systems.

The strategy to reducing DH return temperature through the customer contract has had limited success in Sweden but has had better success in the USA, particularly in district cooling systems. Delta T contract provisions may not be successful due to insufficient incentive in the flow tariff, because they are not well understood by the customer and/or they are simply not enforced. The most effective tools in securing good temperature performance are close cooperation with the customer, good communication, early design input and effective commissioning.

5.3.4 Policy Issues
Harmonization of national fuel taxes and subsidies would facilitate efficient and cost-effective use of REWH. Policies, incentives and tariffs vary significantly from country to country. For example, in 2011 it was reported that district heating companies in Denmark can purchase electricity at a cheap rate when the power grid has excess power due to wind energy production, as long as that electricity is used to heat up energy storage. However, if the electricity instead is used by a heat pump, the electricity is more expensive, resulting in postponement of a large project in Denmark using solar collectors combined with a heat pump.24

Another example concerns individual heat pumps and peak loads. With the growing interest in using smaller heat pumps in single and multi-family houses, it may be economically optimal to design the heat pump for a less than the peak load of the building. District heating could then be used to supply the residual heat, and an appropriate district heating tariff structure can be developed for such a service.
6 Optimization Analysis for Integrating REWH

This section presents an approach for evaluating renewable energy and waste heat options, including economic trade-offs associated with integration of various sources of renewable and waste heat, in the context of not only the costs and technical parameters related to the heat source but also those for the distribution and building systems.

6.1 Framework for Considering REWH Resources

Based on fundamental design criteria in section 5, REWH resources are grouped into categories in Table 4.

<table>
<thead>
<tr>
<th>Availability Characteristic</th>
<th>Temperature Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2.1 Intermittent</td>
<td>High grade</td>
</tr>
<tr>
<td></td>
<td>Low grade</td>
</tr>
<tr>
<td></td>
<td>Below grade</td>
</tr>
<tr>
<td>Dispatchable</td>
<td>Biomass, Bioliquids, Biogas, Municipal solid waste, Geothermal heating*</td>
</tr>
<tr>
<td>Correlated with DES load</td>
<td>Flue gas heat recovery</td>
</tr>
<tr>
<td>Site-specific annual pattern</td>
<td>Deep water cooling*</td>
</tr>
<tr>
<td>Concentrating solar</td>
<td></td>
</tr>
<tr>
<td>Flat plate solar*</td>
<td></td>
</tr>
<tr>
<td>Industrial waste heat*</td>
<td></td>
</tr>
</tbody>
</table>

* Relationship of resource temperature to DES temperatures will vary depending on site-specific circumstances

Table 4. Resource Categories

6.2 Temperature Characteristic Evaluation

6.2.1 Building System Temperatures vs. DES Temperatures

Historically, conventional hydronic building heating systems in North America have been designed for supply/return temperatures of 82/71°C (180/160°F). However, these temperatures are generally higher than necessary, representing design practices from the era of easy energy. As discussed in the prior section, the trend, particularly in Europe, is toward reduced temperatures for exactly the reasons addressed in this report.

Technically, it is possible to reduce supply temperatures for building space heating (SH) systems down to near the desired indoor air temperature (20°C or 68°F). Practically, it makes economic sense to design systems for higher temperatures due to the costs of additional heat transfer area in equipment. There is a trend in Europe toward reducing SH system supply...
temperatures down to the range of 45-55°C (113-131°F). In Canada, most new buildings in Ottawa are now being designed for 47°C (117°F) supply temperatures. In Ottawa, the only buildings that are designing for higher temperatures (approximately 87°C/71°C) are those connected to steam district heating systems.

The risk related to the Legionella bacteria, amoebae and other microorganism growth in domestic hot water (DHW) systems is the key limitation in reducing district heating temperatures. Simultaneous with the publication of this report, IEA is publishing another report which presents the hypothesis that it is possible to heat all types of existing buildings with supply/return temperatures potentially as low as 50/20°C (122/68°F). That report describes research on the energy savings and opportunities that would arise if DHW heating could be reduced to temperature levels close to the end-users real needs (40-47°C or 104-117°F). It notes that a full-scale research project carried out in Sweden in 2011 has demonstrated that a combination of reduced tap water temperatures and bactericidal technology can save energy, while simultaneously enhancing the protection against Legionella.

Instantaneous plate heat exchangers provide a means of removing DHW storage in the building, thereby mitigating Legionella risk.

Beyond the supply temperatures, the return temperatures from building SH and DHW systems are crucial variables for the following reasons:

- For SH, the return temperature in older buildings may be as high as 70°C (160°F). In new buildings, it is perfectly feasible for this temperature to be at or below 30°C (85°F). Experience suggests, however, that consultants and property developers are risk-averse and often use a standard product which is difficult to change. Lower mean temperatures do result in larger HEX, which has a cost impact for the building owner.
- For DHW, the return temperature is the temperature of the water supplied by the municipality, which is generally in the range of 10-15°C (50-60°F).
- For the DES return temperature an “approach temperature” across the heat exchanger must be added. Generally, 3-5°C (5-9°F) and 10-15°C (18-27°F) are economically optimal return approach temperatures (depending on energy prices and case-specific factors) for SH and DHW heat exchangers, respectively.

Thus, after consideration of heat exchanger approach temperatures, any energy resource above 33°C (92°F) can potentially contribute some heat to a low temperature hot water district heating system serving new low temperature buildings. Theoretically, any energy resource above 60°C (140°F) could potentially supply nearly all the total district heating supply temperature requirement for an “low temperature” district hot water system (with supply temperatures boosted from other sources for a relatively few number of annual hours). However, economic considerations for a mixed development will normally push the district heating design peak supply temperature up. The economically optimal level depends on case-specific factors, as further discussed below.
6.2.2 Mitigating Issues Related to Reduced District Heating Temperatures

Pushing district heating temperatures down can exacerbate problems associated with low summer heat demand in district heating networks with low heat densities. DHW demand is discontinuous and generally only required for a few hours per day for any given customer (hospitals are an example of an exception). If proper control strategies are not implemented, the reduced district heating load can cause an undesirable cooling of the network to temperatures that would become insufficient to assure the prompt provision of heat customers call for DHW.

Below are some examples of measures that can be applied for low heat density areas.

Design Considerations

- Design distribution piping systems (DPS) with narrow pipe sizes.
- Use only well-insulated prefabricated DPS.
- Use a narrow temperature approach when designing the DHW heat exchanger (especially important for one-family houses).

Operational Considerations, Higher Temperature

For smaller district heating networks a higher supply temperature can be applied during the low demand period (e.g. June to August). Once flow demands become higher, a lower supply temperature can again be applied. For larger systems where it is impractical and/or costly to raise the supply temperature for the whole system, the supply temperature can be boosted locally at critical customers.

Operational Considerations, Additional Flow

To overcome excessive temperature drop, additional flow can be provided when the supply temperature becomes too low at the end user. There are several methods to increase the flow, and the most common is to install a bypass between the supply and return piping at the critical end users. This method is simple both from an installation and operational standpoint but has the disadvantage that the return water temperature will significantly increase, which causes increased heat loss and possible energy inefficiencies at the heating plant.

Another option to increase the flow is to introduce further “artificial” load requirements such as bathroom towel dryers etc. The idea would then be to utilize the bypass system for this purpose. It is important that this additional load is not added by using DHW water since there are potential risks for bacteria.

6.2.3 DES Temperatures vs. REWH Temperatures

High Grade REWH Source

Evaluation and optimization for utilization of a high grade REWH source should focus mainly on the DES supply temperature rather than the REWH source temperature.

Whenever there is a temperature limitation of the REWH source, the DES supply temperature duration curve (temperature program) should be given careful consideration. It is generally
most economical to design the REWH production for less than the peak demand, and polish the temperature and/or use another source during the relatively few peak load hours.

For an existing DES it should be verified whether or not today’s supply temperature program is a firm requirement or if the supply temperature can be lowered at certain times or all the time. This has to be carefully tested and integrated into operations to ensure consistent customer comfort. This doesn’t mean that this alternative should be rejected immediately at the first customer complaint. It may be worthwhile to implement improvements within some or all customer buildings to achieve the goal.

In general a low DES supply temperature minimizes distribution heat losses, but there may be an economic trade-off in that a reduced delta T increases costs for water distribution, and for building systems if building system improvements have to be implemented.

For a new DES, the design should allow for the most cost effective supply temperature relative to optimal utilization of the REWH.

**Low or Below Grade REWH Source**

Evaluation and optimization for utilization of a low or below grade REWH source should focus both on the DES supply and return temperature vs. the REWH source temperature.

By definition, a low-grade REWH source is sometimes or always insufficient relative to the DES supply temperature but always sufficient relative to the DES return temperature. Given the fundamental physics of coils and heat exchangers, and provided there are no bypasses and/or flow control issues, a higher supply temperature should result in a lower return temperature. This means that there may be situations where it could be beneficial to keep a relatively high DES supply temperature throughout the year in order to achieve a lower return and therefore facilitate additional use of the low grade source. This will also reduce costs for flow distribution and building systems but there is an economic trade-off with respect to higher heat losses in the distribution piping system. An alternative strategy is to polish the DES supply temperature only as required for peak loads.

For an existing DES this has to be carefully tested and integrated. In practice, some systems will experience a rise in return temperature in conjunction with the supply temperature due to poor process control and/or bypasses in the system. This doesn’t mean this alternative should be rejected immediately after the first test. It may be worthwhile to implement improvements within the system and/or customer buildings to achieve the goal.

A below-grade REWH source always has a temperature lower than the DES return temperature and must utilize heat pumps to further extend the temperature range for heat recovery. In using heat pumps, it is of utmost importance to minimize the temperature lift (difference between the source temperature and the goal temperature) to achieve high efficiency.

In using heat pumps, it is of utmost important to minimize the temperature lift (difference between the source temperature and the goal temperature) to achieve high efficiency.
6.3 Availability Characteristic Evaluation

Resources can be grouped in the following categories: dispatchable; correlated with DES load; site-specific annual pattern; and intermittent.

One thing all sources have in common is it is generally useful to integrate them with a thermal energy storage (TES) system. TES facilitates maximum usage of REWH sources when those sources are available, and allows use of this stored energy when required, thereby maximizing use of REWH. For example, in some climates in the spring and fall there are cold mornings and warm afternoons. If the district heating and district cooling systems are integrated, hot water can be used to store afternoon heat recovered from heat recovery chillers for use the following morning. By reducing peak demand, storage systems can also help to increase the load factor for renewable thermal energy systems including biomass boilers (see further discussion regarding assessment and sizing of TES below).

6.3.1 Dispatchable

Examples of dispatchable REWH sources are bioenergy, municipal solid waste, geothermal heating and geoxchange. Dispatchable REWH sources typically have no or only minor integration issues when connecting the source into a DES.

The main concern for implementing a dispatchable REWH source is the control integration between the REWH source and other non-REWH energy sources within the DES. A well-integrated DES system can be programmed to maximize use of the cheaper REWH source. Metering and controls can be a costly portion of the system, but investments in control systems can maximize the operational and economic results. Instrumentation redundancy and data collection should be thoroughly planned.

6.3.2 Correlated with DES Load

Examples of REWH sources that correlate with the DES load are flue gas heat recovery and chiller heat recovery. Common for this group is the importance of an adequate understanding of the load pattern when sizing the REWH source.

For example, flue gas heat recovery will always be dependent on the operations of the boiler providing the flue gas. Sizing of the flue gas recovery system requires a thorough analysis of the operating patterns of the boiler supplying the flue gas.

Chiller heat recovery requires a complete understanding of the daily and seasonal load pattern curves for both the DES heating and cooling systems in order to evaluate the overlap of the thermal loads.

Figure 42 below shows an example of a combined LDC for heating and cooling loads. As further discussed in section 7, thermal energy storage can be an important optimizing technology for a range of REWH resources.
6.3.3 Site Specific Annual Pattern
Examples of REWH sources that follow site-specific annual temperature patterns are deep water cooling and sewage heat recovery. A typical characteristic for these sources is that their availability is lower when the DES load needs are the highest. Consequently, careful consideration must be given to load support from other energy sources during DES peak requirements.

6.3.4 Intermittent
Examples of intermittent REWH sources are wind and solar thermal. Industrial waste heat recovery is typically available on a schedule coinciding with the operations of the industrial plant, but can be subject to unplanned outages.

A typical characteristic for intermittent sources is the unreliable nature of the resource supply. As a result, careful consideration must be given to readily available backup from other sources for critical loads.

Short-term thermal energy storage is often sufficient to address intermittency. However, solar thermal is not only intermittent but also generally less available when heating needs are greatest. In this case seasonal thermal energy storage can be considered.

Figure 42. Example of Combined LDC for Heating and Cooling Loads
6.3.5 Assessing Short-Term Thermal Storage

Short-term thermal storage systems are designed to be recharged on a cyclical basis (usually daily but in some instances weekly). Thermal energy storage can fulfill one or more of the following purposes:

- **Increase system capacity.** Demand for heating, cooling, or power is seldom constant over time, and the excess generation available during low demand periods can be used to charge the TES system in order to increase capacity during high demand periods. For example, cooling storage allows a district cooling system to install less chiller capacity and to use the installed capacity at a higher load factor.

- **Enable dispatch of CHP plants.** CHP plants are generally operated to meet the demands of the connected thermal load, which often results in excess or insufficient electric generation. By incorporating TES, the plant can be dispatched within some limits.

- **Shift energy purchases to low demand/low cost periods.** Cooling storage allows operation of chillers in a district cooling system to shift electricity demand from costly day-time on-peak periods to lower-cost night-time periods.

- **Increase system reliability.** TES increases the flexibility and reliability of the DES by ensuring that there is a readily available source of energy which can be supplied to users with only a minimal requirement of pumping energy.

Hot water storage is commonly used in European district systems while in the USA thermal storage is most common in district cooling systems.

6.3.5.1 Short-Term Hot Water Storage

Short term hot water storage is typically sized for a few hours up to a week of storage. Most common are atmospheric tanks but for some systems a pressurized tank is required due to the DES temperature or pressure regime (typically above 100°C or 212°F).

Figure 43 shows a hot water thermal storage tank (in Europe usually called an accumulator).

Over and above the main purposes described above, the storage can also act as a pressure holder in the DES as well as taking care of expansion.

Crucial for TES sizing is the DES delta T because a high delta T will allow more energy to be stored with less water volume. A hot water storage tank will therefore always be much smaller for the same amount of energy compared to a chilled water storage tank.
6.3.5.2 Short-Term Chilled Water Storage

The daily variation between maximum and minimum loads for cooling is much greater than for heating. Building cooling systems are usually operated more on/off than heating systems. During nighttime when the ventilation air to an office can be shut off, the outdoor temperature is lower and there is less internal heat gain, so the cooling system can be shut off. In contrast, a heating system is generally operated at night. With the on/off operation of building cooling systems, a morning peak can occur when the buildings are cooled down before office hours. However, the cooling load profile for a specific system depends on weather conditions, types of buildings served, operation of the building cooling systems and the DES rate structure.

Cool storage can be provided through storage of chilled water, ice or ice slurry. Where space is available for chilled water storage, the economies of scale for this technology can provide significant economic advantages over ice storage.

Chilled water is the most common form of cool storage, using concrete or steel tanks to store the water. Chilled water is typically stored between 4-7°C (40-45°F) in one large or several tanks located above ground or below ground. Under normal conditions a chilled water storage tank is always filled with water. During discharge, cold water is pumped from the bottom of the tank and warm return water is supplied in the top. Due to the different densities for water at different temperatures a stable stratification can be obtained.

Ice generation and storage is a well-developed technology, and allows storage in a more compact space -- often a key issue in urban environments. The volume required for ice storage is 15-25% of the space required by chilled water storage for the same energy storage capacity. Ice storage also provides an opportunity to reduce the temperature of cooling distribution and
therefore reduce distribution system and building system capital costs. These advantages must be weighed against higher capital and operating costs for ice-making equipment compared to water chillers. The average capital costs of ice storage are about twice those of chilled water storage, and the energy requirements are higher by about one third.\textsuperscript{26}

### 6.3.6 Assessing Seasonal Storage

Aquifer Thermal Energy Storage (ATES) is an open-loop geothermal technology. It relies on seasonal storage of cold and/or warm groundwater in an aquifer. The technology was developed in Europe over 20 years ago and is now in use at over 1,000 sites, mostly in the Netherlands and Scandinavia. Although ATES is highly efficient and very "green," it is not a renewable energy technology as it is used for energy conservation, not energy production. However, ATES is often used in conjunction with renewables, such as use of solar hot water panels to create hot water for storage in summer, and with solar- or wind-powered electricity to power the mechanical components of an ATES system.

ATES requires a suitable aquifer, into which at least two thermal wells are installed. Other components of an ATES system include heat exchangers, distribution piping, and mechanical systems and controls necessary to integrate an ATES system with a DES.

In ATES cooling systems, during cold winter weather, groundwater is pumped through a simple heat exchanger where it is cooled down, and stored in a designated "cold store" portion of an aquifer. Cold groundwater is recovered from the cold store during summer months and used for cooling. After the water has been used for cooling, it has been warmed and is injected into the designated "warm store" portion of the aquifer. The cycle is repeated seasonally. See Figure 44\textsuperscript{27} which shows the aquifer storage system at Arlanda Airport in Sweden.

![Figure 44. ATES at Arlanda Airport, Winter (left) and Summer (right) Operation](image)

The initial design and construction costs tend to be relatively high due to the costs of well drilling and the significant hydrogeologic and engineering knowledge required to design an ATES system. ATES needs a reasonably large site to have enough room for both a cold and a warm store. Also, because an ATES system relies on groundwater injection and withdrawal through wells, care must be taken to avoid geochemical or operational conditions that could foul the well screens.
There are normally strict permitting requirements for an ATES system; however the net environmental benefit and the unobtrusive nature of its operation can help facilitate timely approvals. Groundwater is not chemically altered in an ATES system - therefore the only regulated parameter of concern is temperature. Accordingly, the design of the ATES system should strive to minimize subsurface thermal impacts at the property line.
7 Recommendations

7.1 General Recommendations

This section provides recommendations for maximizing the cost-effectiveness, efficiency and benefits of integration of REWH with DES. The first part of this section covers general recommendations that are applicable to a range of resources, including summary recommendations regarding the impact of district energy supply and return temperatures on accessibility of energy resources, trade-offs between plant, distribution and building system investments, and monitoring and control of systems. The second part of this section addresses resource-specific recommendations.

Clearly the following discussion is generalized. Given the multitude of variables in any specific project, it is essential to conduct a detailed analysis and design for each project.

7.1.1 Confirmation of Goals

Whether the DES system is new or existing, it is appropriate to start any analysis of integration of REWH by confirming the goals to be achieved and the relative emphasis that should be placed on each goal. Goals may include, for example:

- Reduction in emissions of greenhouse gases (GHG) or other environmental impacts.
- Reduction in costs.
- Increased flexibility to respond to future changes in supplies and/or prices of fossil fuels.
- Local economic development.
- Public relations.

The relative importance of these goals can influence key parameters in the analysis, such as the discount rate for Net Present Value (NPV) analysis.

7.1.2 DES Loads and Temperatures

It is essential to model the DES loads, ideally on an 8760 hour basis, relative to both energy and temperature. In an existing DES system operating data can inform this analysis. For integrated district heating and cooling systems it is especially critical to understand when heating and cooling loads occur simultaneously or within a 24 hour period.

To the extent that data allows, it is useful to examine how each of the customers contributes to the delta T performance of the system. For an existing hot water system individual customers can be ranked based on their annual “overconsumption” of water against a reference delta T, which is a direct measure of their temperature influence on the total system. Once this has been performed it should be determined how much each customer costs the district heating company due to this overconsumption of water. This is useful for later determination of potential trade-offs between investments in plant, distribution capacity and building systems.

If existing buildings are to be served with a low temperature hot water system, it is important to test each building, or a sampling of representative buildings, at low supply temperatures to determine return temperature performance. This is critical to understand building conversion
needs. Practical limitations in retrofitting buildings can constrain the potential to serve such buildings with low-temperature resources.

For a new DES, the choice of DES temperature regime is extraordinarily important. As discussed further under “Life Cycle Economic Analysis” this requires a thorough comparative analysis of the capital and operating costs of options relative to:

- Energy resources.
- Distribution systems.
- Building ETS designs.
- Building heating/cooling systems.

7.1.3 Resource Assessment

REWH resources must be assessed relative to:

- Quantity of energy potentially available.
- Temperatures.
- Availability and reliability of energy supply.
- Capital costs.
- Heat or fuel price.
- Other operation and maintenance costs.

Multiple REWH resources can be more effectively integrated by designing the production systems to allow use of higher-temperature resources to polish lower-temperature resources.

It is also important to fully assess the maturity of the required technologies. It is preferable to safely achieve the fundamentals versus risking the brand name and/or the environment for a large prestige project that uses non-commercial technology that has not been proven or is overly complex. Depending on the goals being pursued, it will likely be more advisable to prioritize the simple, known, small, and thus secure (but with slightly lower profitability) technologies rather than the highly advanced (with great theoretical profitability) approaches. The integration can then be gradually built out with higher efficiency, innovation and expansion.

7.1.4 Integrated Assessment

There can be significant benefits in combining multiple REWH sources in a DES to the extent that the temperature and availability patterns of the sources complement each other. On the other hand there is also a risk in combined REWH sources to the extent that one source could displace another if the integration has not been thoughtfully considered. The primary task therefore, is to integrate the various forms of REWH in order to achieve the optimal utilization of sources.

A fundamental consideration is the role of base load sources vs. peak load production units. Typical characteristics for base load and peak load production units can be summarized as follows:

**Base Load Units**

- High construction cost.

- Low fuel cost.
- Substantial environmental impact before cleaning.
- Poor modulation ability.
- Require substantial start-up time.

Peak Load Units

- Low construction cost.
- High fuel cost.
- Moderate environmental impact.
- Good modulation ability.
- Limited requirements relative to start-up time.

7.1.5 Monitoring and Controls

Recommendations relative to design of monitoring and control systems include:

- Monitoring of key operating parameters, such as temperatures, flow rates, pressures and efficiencies, is essential in order to detect and solve operational problems and optimize the system hardware and operational strategies.

- In any system involving electricity production and/or consumption (e.g., systems using CHP, use of wind as a grid balancing method, heat recovery chillers, geoxchange or other heat pumps) a predictive economic dispatch model of the production sources is essential to provide guidance for the plant operators. Such a system should advise the operators, on at least a 24 hour-ahead predictive basis, of the expected prices of imported electricity, exported electricity and thermal energy sources. Operators can then make decisions on planning for the following day relative to:
  - how much electricity to generate;
  - how much electricity to import from the power grid;
  - thermal production sources;
  - charging or discharging chilled water storage; and
  - charging/discharging hot water storage

- It is important to note that while some plant operations could be automated, the most important decisions should be made by trained, licensed human operators. Those decisions should be made based on the following criteria: safety, legal and regulatory, reliability, environmental impact, and life cycle cost.

- Instrumentation redundancy and data collection should be planned at the onset of a project. A set of commonly needed data points should be determined by all parties involved.

- Real time software simulations of the district heating network can help minimize heat losses and pumping energy consumption to ensure the lowest possible environmental impact, for the following reasons:
  - Hydraulic simulation of the system allows faster detection of malfunctions and assesses the potential for improvements in the district heating network;
  - Supply temperature optimization ensures that the supply temperature is always as low as possible considering both the accumulated energy in the distribution system and changes needed as a result of the weather forecast; and
Remote monitoring of Energy Transfer Stations (ETS) allows for detection of malfunctions and improvement of customer performance, e.g. reduction of return temperature.

### 7.1.6 Resource Contracts

For any given REWH project, transparency is a key to ensure win-win solutions for the seller and buyer of thermal energy. Price structures should take into account the temperature of the thermal energy as well as its availability and reliability. Both temperature and availability have a great impact on the need for peak and backup capacities which must be reflected in the price structure. Contracts between the heat distribution network and privately owned CHP plants should allocate fuel cost savings arising from CHP production versus separate heat and electricity production to the participating parties based on relative risks relating to financing the investment and operating the system. Contracts should also address allocation of future benefits arising from new fiscal policies or incentives if they arise during the period of the agreement.

For DES systems procuring thermal energy from multiple outside sources it is important to develop a policy and operational strategy for right of precedence for energy delivery into the district scheme. Contracts for resource acquisition should be carefully crafted to ensure that operational dispatch is guided by a clear set of economic and environmental objectives, with clear provisions to limit acquisition of third party resources in order to meet those objectives.

### 7.1.7 Customer Contracts

It is important to ensure low return temperatures in order to maximize efficiency and realize thermal storage design capacity. If new buildings are to be served, it is important to provide building system design guidance and review to ensure that the system provides the lowest possible return temperature.

Customer tariffs should incorporate economically transparent price signals to encourage higher delta T. Such provisions can take a number of forms. The customer contract can establish a target district water flow per unit of district heating or cooling energy purchased, with a penalty per unit of water flow in excess of the target. A “carrot and stick” approach can be taken, establishing a range of targeted flow, above which there is a penalty and below which an incentive payment is made.

During the operational phase, it is also useful to provide technical advice to customers to help them operate to provide the lowest possible return temperature.

### 7.1.8 Life Cycle Economic Analysis

Good decisions about integrating REWH in DES require a thorough comparative analysis of the capital and operating costs of options relative to:

- Energy resources.
- Distribution systems.
- Building ETS designs.
- Building heating/cooling systems.
The task is made more complex because the analysis should not only address the near term but also future growth and evolution of the system. In this regard it is important at the outset to assess the potential energy resources in the community and how price and technology trends might affect the future viability of those resources for the DES.

Examples of cost trade-offs include:

- Higher plant capital costs to achieve higher efficiency (e.g., solar collector efficiency, heat pump COP) vs. saved costs for energy otherwise purchased.
- Higher distribution system capital and operating (pumping) costs for a lower temperature district heating system vs. reduced plant capital and operating costs to produce lower temperature heat.
- Reduced operating costs to obtain low temperature heat vs. increased investment in building systems.

The appropriate financial analysis framework will vary between DES systems depending on ownership, financial resources and financing policies. For example, a for-profit company will likely project the return on equity (ROE). A public or non-profit entity may use Net Present Value (NPV) analysis as a decision-making tool.

Policy-makers should note that increased certainty and stability of long-term policies and incentives will encourage investors to construct infrastructure for integrating REWH.

7.2 Resource-Specific Recommendations
This section describes resource-specific considerations for each REWH and addresses technical and economic parameters, lessons learned and key issues for integration with a new or existing DES. An overview of key resource-specific issues is provided in Table 5. Apart from specific technical and economic parameters it is of general importance to identify and evaluate resource-specific risks and associated consequences in terms of technical maturity and economic scale factors.
## 7.2.1 Bioenergy

Bioenergy can be classified as a dispatchable and high grade source, which makes it a useful source for DES integration. When planning a biomass project, it is important to focus attention on ensuring a fuel supply of sufficient quality and quantity. This is particularly important if the planned fuel is urban waste wood, due to its variability and the potential geographic spread in the location of the resource. If fuel is to be procured from outside suppliers it should be done under very tight contracts relative to fuel quality, particularly moisture, particle size and non-combustibles. Additional processing may be required to avoid materials handling problems due to oversize particles. Depending on location, seasonality of supply can be a big issue, so adequate storage is important. Fuel should be purchased based on the energy contained in the fuel or on a dry basis (price per dry ton of fuel).

Regulation of emissions from biomass combustion can vary substantially from country to country, so a thorough understanding of how the regulations classify a given biomass material is critical.

Financial analysis of bioenergy projects should assess potential long-term competition for biomass fuel/feedstock and analyze the sensitivity of project feasibility to long-term increases in fuel/feedstock costs.

### Table 5. Overview of Key Resource-Specific Issues

<table>
<thead>
<tr>
<th>Resource</th>
<th>Resource-specific Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>Addressing long-term risks associated with adequate supply of economical fuel meeting the design fuel specification.</td>
</tr>
<tr>
<td>Biogas</td>
<td>Gas quality and suitability for systems.</td>
</tr>
<tr>
<td>Bioliquids</td>
<td>Fuel quality and suitability for systems.</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>NIMBY (&quot;Not In My Back Yard&quot;). Distance from plant to load.</td>
</tr>
<tr>
<td>Geothermal</td>
<td>Adequate understanding of long-term flow and temperature characteristics of the geothermal resource.</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>Intermittency.</td>
</tr>
<tr>
<td>Wind</td>
<td>Intermittency.</td>
</tr>
<tr>
<td>Deep water cooling</td>
<td>Ensure true understanding of temperatures seasonally and at given depth. Robust design for cleaning of intake.</td>
</tr>
<tr>
<td>Geo-exchange</td>
<td>Site requirements.</td>
</tr>
<tr>
<td>Chiller heat recovery</td>
<td>Adequate understanding of cooling and heat loads thermal overlap.</td>
</tr>
<tr>
<td>Sewage heat recovery</td>
<td>Appropriate design and practices for maintenance of heat exchangers.</td>
</tr>
<tr>
<td>Process waste heat recovery</td>
<td>Adequate understanding of the long term existence of the industrial source.</td>
</tr>
<tr>
<td>Flue gas heat recovery</td>
<td>Adequate understanding of physical and chemical impact of gas streams on heat exchangers. Emissions control of condensing heat recovery air effluent.</td>
</tr>
</tbody>
</table>

---

94
Commercial biogas production must not only ensure a sufficient supply and quality of upstream waste substrate, but also adequate downstream demand for biogas.

### 7.2.2 Municipal Solid Waste

Municipal waste to energy (WTE) can be classified as a dispatchable and high grade source, although from a design perspective there can be benefits in reducing the temperature of recovered heat from a CHP optimization standpoint.

Generally, a key challenge with integrating municipal solid waste is the distance between the plant and the DES loads. Typically, waste management facilities are located far from the denser development areas served by a DES. The prospect of construction of a new WTE plant is an entirely different challenge than retrofitting an existing WTE power-only plant to recover heat (such as the Coventry UK system discussed in section 4).

In North America development of WTE plants has been constrained by the relative abundance of cheap landfills, fears that plants could undercut recycling programs, and negative public perceptions of WTE. The “Not In My Back Yard (NIMBY)” mentality can be a significant challenge. Involving residents in the planning process from the outset, as well as providing them with information about the scheme and opportunities to have their questions answered, is essential in order to gain residents trust.

Generally, in Europe NIMBY constraints are less significant. Many countries that are expanding WTE capacity, like Sweden, Denmark and Germany, typically also have the highest recycling rates; only the material that cannot be recycled is burned.

Other potential considerations when evaluating municipal solid waste are:

- If an existing coal-fired boiler is being modified to use processed refuse (Refuse-Derived Fuel or RDF) as a fuel, fouling of heat transfer surfaces and corrosion can create major issues and need specific consideration.
- Life cycle GHG analysis of WTE should consider transportation of the waste material to the plant in comparison with other alternatives.

### 7.2.3 Geothermal Heating

Geothermal heating can be classified as a dispatchable source. Depending on location-specific resource temperatures, geothermal heating can be used for a wide range of loads, even production of electricity and heat with CHP.

A key economic issue with geothermal energy systems relates to the relatively large initial investment in drilling and the technical risks of not finding enough hot water. It is also critically important to have adequate understanding of long-term flow and temperature characteristics of the geothermal resource.

If a Kalina cycle is used for power generation, it is important to pay particular attention to the design of the steam separator, condenser and turbine interior design in order to ensure 100% separation of fluid and steam. Otherwise this can lead to damage to the turbine blades.
7.2.4 Solar Thermal

Solar thermal can be classified as an intermittent and low (or high) grade source. Solar thermal availability generally has an inverse relationship to the heating load needs. This is true not only on a seasonal level but also on daily pattern. Hence hot water thermal storage and/or an oversized heat sink (district heating distribution system) will help maximum utilization.

When sizing a solar thermal system from a DES integration design perspective:

- Low district heating supply temperature is essential since collector performance deteriorates with higher temperatures.
- District heating summer load requirements will typically determine the maximum limit for sizing of a solar thermal system.
- TES provides an opportunity for solar system optimization, so solar system sizing is highly interactive with the TES design.

Important technical and economical parameters to be given careful consideration when evaluating a solar thermal system are:

- Full backup is essential due to the intermittent nature of the source.
- Siting of solar collectors is critical relative to space needs, visibility and acceptance.
- Care must be taken in positioning of the solar collectors (horizontal angle and orientation, shading or adjacent obstructions).

Solar thermal installation can typically be integrated with a DES in one of two ways: integrated with the rooftops of customer(s); or a stand-alone plant. Integration with a customer yields pipe construction cost benefits since no additional service lines are required. However, this alternative requires DES-compatible supply temperature if/when heat is to be exported to the DES. For a DES system with a high supply temperature requirement this could require more expensive solar collectors (e.g., evacuated tube vs. flat panel).

A stand-alone plant can be used for preheating of the DES return water and hence benefit from cheaper collectors and better performance but would obviously require additional piping installation. A ground-standing plant is generally significantly less expensive than rooftop installations, but this is dependent on the availability and cost of land.

Other solar thermal integration considerations are summarized below.

**Mechanical Design**

- In projects with multiple roof installations, target matching elevations to the greatest possible extent to avoid challenges with filling, venting, and isolation.

**Equipment Selection**

- It is important to carefully select the solar collectors. As discussed in section 4 and in the St. Paul Solar Thermal case study in Appendix 1, collector performance (and related energy production) is a crucial aspect of project feasibility.
• Although there are many high-performing international manufacturers, shipping and unloading large collectors can be a challenge. Project developers should identify local offsite delivery points for local pickup and delivery responsibility by the contractor. This can avoid unnecessary delays, and hidden costs associated with import, ocean transport, rail and unplanned storage.

Structural

• Structural vulnerabilities may contribute significant additional costs. Solar projects should be identified prior to building construction for optimal savings. Projects involving installations on existing buildings should carefully investigate structural integrity and reinforcement costs.
• Roof age should be taken into consideration. Solar projects are ideally planned with new construction or a re-roofing project.
• Maximum crane access to the installation site minimizes time constraints, planning, and construction costs. The handling and storage of large collectors can also pose a challenge if not considered during site evaluation.

Controls

• Proper control installation and data collection is essential for maximizing the potential energy return. Control software should be programmed to take advantage of low grade heat prior to reaching elevated temperatures. Preferably, it should also read and anticipate solar irradiation to determine optimal operational modes.
• Control installations should maximize integration between existing building controls and additional solar controls. If the systems are well-integrated the conventional system could be programmed to anticipate and to a greater extent accommodate solar energy and maximize available energy. A pyranometer (solar irradiance reading) is used to control changes in operational modes such as startup, export mode, etc.
• If solar panels are installed on roofs of customer buildings, consider designing the system to use solar output to meet that customer’s requirements first, with export of excess solar heat to the district heating system. The thermal load and temperature characteristics of the host customer building(s) should be carefully studied before implementation. There will be periods when the solar output is only enough for the building. If the host building requirements can be met with low temperature solar production, a higher collector panel net efficiency will result since collector performance deteriorates with higher temperature.

7.2.5 Wind

Wind can be classified as an intermittent and high grade source. Wind is relevant to DES primarily in the context of integration of DES with power grids as a power load balancing strategy. Since the variable cost of wind energy is very low it is able to displace most types of thermal power production, with the result that wind turbines and CHP plants will compete for an electricity demand. As a result there will be pressure on CHP plants to reduce combined generation. CHP plants however have the potential to serve the increased demand for balancing services caused by wind power if steps are taken to facilitate utilization of the
flexibility already present in the DES. Specifically, hot water systems can absorb large quantities of electricity by using for example heat pumps and/or immersion heaters.

7.2.6 Deep Water Cooling
Deep water cooling can be classified as a site specific annual pattern and low to high grade source depending on site-specific resource temperatures.

Prior to design, it is important to implement a monitoring program to determine (or corroborate other data on) lake or sea water temperatures at various depths at the project site. Deep water cooling is heavily dependent on a stable and predictable range of the maximum depth of the thermocline and a large enough water volume below this depth. Existing data may not accurately represent the actual temperature regime in the sea/lake and a water temperature monitoring program may often be required. This will help avoid later design changes to, for example, extend pipe further in order to reach the desired water temperatures.

It is important to assess if the deep water cooling system could have a biodiversity impact and an environmental study is normally required to ensure the ecosystem will not suffer (e.g. specific fish species etc). In the case of Lake Ontario (see Enwave case study) they found the impact of the project was beneficial for the fish ecosystem as well as the City’s drinking water quality.

7.2.7 Heat Pump Technologies
When sizing a heat pump system from a DES integration design perspective the following general considerations are important:

- Low temperature difference between the heat source and heat sink is essential since heat pump efficiency deteriorates with high temperature difference.
- Available heat pumps on the market have a limited supply temperature, so lower DES temperatures could be a requirement for integration.

Hot water supply temperature plays a major role in heat pump systems since the efficiency decreases with high supply temperature. For a system serving a mix between new and old buildings it is imperative to find the optimal district system supply temperature, striking a balance between heat pump efficiency and achievable temperatures in buildings. An analysis must be undertaken to compare the cost-effectiveness of: retrofitting buildings so that their requirements can be served at lower supply temperatures; and/or supplying supplemental heat with a peaking boiler. For Ball State University it was found that at a supply temperature of 65°C (150°F) struck the optimum balance (see case study).

For reference, custom made heat pumps can provide output heat up to 80°C (175°F) whilst a standard type heat pump can produce a maximum of 55-60°C (130-140°F). These temperatures are relatively close to the return temperatures in high and low temperature hot water systems, so integrating low grade sources at a large scale can be a challenge and may require extensive modifications within buildings’ HVAC systems. Heat pumps are often more suitable for areas with new buildings that are designed to lower temperature requirements.

Other important technical and economic parameters to be given careful consideration when evaluating heat pumps are:

- Estimation of heat pump seasonal efficiency.
- Electric power grid characteristics.
- Method of evaluating environmental impact.

**Geo-Exchange**

Geo-exchange can be classified as a dispatchable and below-grade source. Important technical and economic parameters to be given careful consideration when evaluating geo-exchange are:

- Hydrogeological and geochemical description of the site.
- Environmental regulatory acceptance.
- Location and space requirements.

Closed loop systems require multiple boreholes and, if not sized properly, may raise underground temperatures over time, cutting efficiencies in the cooling cycle. Open loop geothermal requires fewer wells but there are more issues with corrosion, particulate filtering and potential groundwater contamination. Early interactions with environmental regulatory agencies are important to gain timely approvals.

**Chiller Heat Recovery (HRC)**

HRC can be classified as a DES-load-correlated, below-grade source. When sizing a HRC system from a DES integration design perspective it is essential to adequately understand the 8760 hour patterns of cooling and heat loads, including their overlap. There must be a coincident cooling and heating load or thermal storage is required.

It may seem intuitive to integrate HRC on the return line of a DES system, which allows for higher efficiencies. However, this option is often limited to situations when the cooling and heating production is located in the same physical location; if not, water flow constraints can be a limiting factor. In most DES systems there is a set-back supply temperature which facilitates integration with the DH supply.

**Sewage Heat Recovery**

Sewage heat recovery can be classified as a site-specific annual pattern, below-grade source. A key consideration when integrating sewage or sewage treatment effluent is ensuring adequate sewage flows vs. DES heat demand variability. Thermal storage may be a useful optimization technology. Permitting processes may also be a challenge. If untreated sewage is used, it is critical to design for maintenance to ensure clean heat exchange surfaces.

It is useful to consider using the cold sewage stream after heat pumps for district cooling.
7.2.8 Industrial Waste Heat Recovery

Industrial waste heat recovery can be classified as an intermittent resource which can be low or high grade depending on case-specific circumstances. The investment in the piping system to link the industrial source with the DES is a key capital cost issue and related risk issue.

In designing the business arrangement between a DES and an outside industrial supplier of waste heat, it is essential for the contract to incorporate a transparent and clear picture of economic risks and rewards. Business risk analysis should address short term consequences of sudden shutdown as well as long term costs to finance alternative base load supplies. The analysis should consider:

- Capital investments by each party.
- Net operational cost reduction compared with alternative fuel costs.
- Profit for each actor in relation to risk exposure.
- Heat supply pricing in relation to delivery commitment.

Industrial companies are increasingly motivated to make a profit on their waste heat or find an internal use for the energy. However, most industries are primarily concerned with maintaining their operations without disruption and require someone else to take the risk of providing adjacent customers with heat. The heat recovery installation should not under any circumstances disturb the production and/or create any production line shutdowns. Technical design as well as contractual arrangements should focus on production reliability issues.

A higher heat price typically creates the foundation for an attractive win-win solution and minimizes the risk for a failure. The pricing of waste heat should account for any lost operating margin or inefficiency arising from the removal of this heat (if any). Beyond that the benefit should reside with the party bringing investment (in heat recovery plant and networks) in order to underpin any business case. There are examples where a low price is unsustainable. The industry may simply get tired of “give away” the heat whilst the district heating company takes “excessive” profit even though they may have funded the facility. District heating companies may lack preparedness and financial reserves to handle sudden economic downturns and industrial closures.

Important technical parameters to be given careful consideration when evaluating industrial waste heat recovery are:

- Heat exchanger materials selection is an important design consideration for industrial waste heat recovery because corrosive gases can quickly degrade heat exchangers.
- Corrosion and oxidation reactions are accelerated dramatically by temperature increases. Advanced alloys or composite materials must be used at higher temperatures.
- If the source is intermittent, the heat exchanger (HEX) may be exposed to both high and low temperatures and it becomes important to ensure that the HEX material does not fatigue due to thermal cycling.
7.2.9 Flue Gas Heat Recovery (FGHR)

FGHR can be classified as a DES-load-correlated, low-grade source. When integrating FGHR into a DES it is important to:

- Design the system based on flue gas latent heat content, temperature and dew point versus available DES return temperature, because available waste heat decreases with temperature (especially if flue gas condensation cannot be achieved).
- Size the FGHR based on the operating pattern of the boiler supplying the flue gas.
- Ensure that the boiler is operating as the DES base load to maximize heat recovery.
- Develop a good understanding of physical and chemical impact of gas streams on heat exchangers (heat exchangers designed from inappropriate low-cost materials will quickly fail due to chemical attack).
- Design for adequate emissions control of condensing heat recovery water and air effluent.

Integrating flue gas heat recovery in a CHP system using the DES as the heat sink requires special consideration from an economic perspective. With steam cycle CHP, more electrical power can be generated and higher efficiency attained with a large heat sink and low temperature. However, introducing flue gas heat recovery as a heat source for the DES can reduce the available heat sink and hence the electrical power generation. This may still be a good solution depending on fuel prices compared with the market value of electricity, but nevertheless it is a key issue that must be considered.
8 Abbreviations and Key Definitions

8.1 Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHU</td>
<td>Air Handling Unit</td>
</tr>
<tr>
<td>ATES</td>
<td>Aquifer Thermal Energy Storage</td>
</tr>
<tr>
<td>Barg</td>
<td>Bar Gage</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>COP&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Coefficient of Performance (Cooling)</td>
</tr>
<tr>
<td>COP&lt;sub&gt;h&lt;/sub&gt;</td>
<td>Coefficient of Performance (Heating)</td>
</tr>
<tr>
<td>DES</td>
<td>District Energy System</td>
</tr>
<tr>
<td>DC</td>
<td>District Cooling</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
</tr>
<tr>
<td>DHC</td>
<td>District Heating and Cooling</td>
</tr>
<tr>
<td>DHW</td>
<td>Domestic Hot Water</td>
</tr>
<tr>
<td>DPS</td>
<td>Distribution Piping System</td>
</tr>
<tr>
<td>EFW</td>
<td>Energy From Waste</td>
</tr>
<tr>
<td>ETC</td>
<td>Evacuated Tube Collectors</td>
</tr>
<tr>
<td>ETS</td>
<td>Energy Transfer Station</td>
</tr>
<tr>
<td>FGHR</td>
<td>Flue Gas Heat Recovery</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>GSHP</td>
<td>Ground Source Heat Pump</td>
</tr>
<tr>
<td>HDPE</td>
<td>High Density Polyethylene</td>
</tr>
<tr>
<td>HEX</td>
<td>Heat Exchanger</td>
</tr>
<tr>
<td>HRC</td>
<td>Heat Recovery Chiller</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>kW</td>
<td>kiloWatt</td>
</tr>
<tr>
<td>LDC</td>
<td>Load Duration Curve</td>
</tr>
<tr>
<td>LFG</td>
<td>Landfill Gas</td>
</tr>
<tr>
<td>MMBtu</td>
<td>Million British Thermal Units</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
</tr>
<tr>
<td>MW</td>
<td>MegaWatt</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>MWH</td>
<td>MegaWatt-hour</td>
</tr>
<tr>
<td>NIMBY</td>
<td>Not In My Back Yard</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
<tr>
<td>OAT</td>
<td>Outdoor Air Temperature</td>
</tr>
<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
</tr>
<tr>
<td>Psig</td>
<td>Pounds per Square Inch Gage</td>
</tr>
<tr>
<td>RDF</td>
<td>Refuse Derived Fuel</td>
</tr>
<tr>
<td>REHC</td>
<td>Renewable Energy Heating and Cooling</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Source</td>
</tr>
<tr>
<td>REWH</td>
<td>Renewable Energy and Waste Heat</td>
</tr>
<tr>
<td>ROE</td>
<td>Return on Equity</td>
</tr>
<tr>
<td>SCOP</td>
<td>Seasonal Coefficient of Performance</td>
</tr>
<tr>
<td>SH</td>
<td>Space Heating</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Energy Storage</td>
</tr>
<tr>
<td>TPA</td>
<td>Third Party Access</td>
</tr>
<tr>
<td>TR</td>
<td>Tons of Refrigeration</td>
</tr>
<tr>
<td>ΔT or delta T</td>
<td>Temperature difference (typically between DPS supply and return temperatures)</td>
</tr>
<tr>
<td>WTE</td>
<td>Waste-To-Energy</td>
</tr>
<tr>
<td>WWTP</td>
<td>Waste Water Treatment Plant</td>
</tr>
</tbody>
</table>
8.2 Key Definitions

The IEA (2006e) defines **Renewable Energy** as energy derived from natural processes that are replenished constantly. This definition applies to a wide range of energy sources derived directly or indirectly from the sun including solar, hydro, wind, wave, biomass and ambient heat, but also includes non-solar sources such as geothermal, tidal and ocean currents.

**Waste Heat** is the energy content of any heat source that is converted/ transferred into useful heat that would otherwise not be used.
9 Appendices – Case Studies
9.1 Ball State University

Muncie, Indiana, USA

University converts from fossil fuel based steam generation and conventional chillers to ground source heat pumps (geoexchange) producing hot and cold water.

Sustainable Energy Technologies
Geoexchange

Organization and History
Ball State University opened in 1918 and has expanded to include 47 major buildings within a campus area of 2.7 km² (660 acres).

The campus has used fossil fuel (coal/oil/gas) fired boilers since the early 1940’s. However, faced the need to replace boiler capacity, the university began to evaluate other energy options. This led to the decision to convert the campus to a more efficient geoexchange heating and cooling system.

District Heating and Cooling System
Ball State University has built the nation’s largest ground-source closed-loop district heating and cooling system. Construction started in 2009 and water began flowing through the system in the spring of 2012. Later the same year, the geothermal system was cooling 47 buildings and heating 22 buildings.

The geothermal heat pump uses the Earth as either a heat source when operating in heating mode or a heat sink (dissipating heat) while in cooling mode. At two geoexchange plants, heat drawn from the ground or returned to the ground is transferred, or exchanged, with heat pumps connected to the district cooling and district heating loops that serve the campus.

Chilled Water (CW) is distributed at a supply temperature of 5.5°C (42°F) and the Hot Water (HW) is distributed at a supply temperature of 65°C (150°F). The low HW supply temperature ensures high seasonal heat pump efficiency and provides flexibility for adoption of new energy supply technologies and innovations that may develop in the future (see further discussion below).

The district cooling (DC) and district heating (DH) distribution systems consist of a total of 12,000 trench meters (39,000 trench feet) of supply and return piping. While the DC system was an extension of an already existing system, the hot water DH system is all new and replaces an aging steam system. For the CW piping extension the University used un-insulated high density polyethylene (HDPE) piping. Ductile iron pipes with pour-in-place insulation were installed for the HW piping.

Additional benefits when converting the campus steam distribution system to hot water, beyond facilitating the deployment of geothermal system, include the following:
• Heating system distribution losses will be substantially reduced;
• Operation and maintenance costs will be much lower;
• Substantial capital costs for replacement of aging portions of the steam system will be avoided through the conversion; and
• Capital costs for future system expansion and interconnection to new buildings will be much cheaper.

The project also required modifications within a total of 540,000 m2 (5.8 million ft2) of campus buildings to provide connectivity to the DC and DH systems as well as temperature control changes in existing air handling units.

**Sustainable Energy Integration**

The geothermal project is part of Ball State’s long-standing commitment to sustainability and, by taking the aging fossil fuel boilers offline, will result in an annual emissions reduction of approximately 75,000 tons of carbon dioxide, 1,400 tons of sulfur dioxide, 240 tons of nitrogen oxide, 200 tons of particulate matter and 80 tons of carbon monoxide.

**Geoexchange**

Once fully built out, the underground closed loop will consist of 3,600 double looped boreholes, each 120-150 m (400 - 500 feet) deep.

During Phase 1 (2009-2012), 1,800 boreholes were installed on the north side area of campus. Work has begun on Phase 2, which includes installation of 780 of the remaining 1,800 boreholes in a field on the south area of campus, and construction will continue throughout 2013-2014.

Each plant (North and South) will include 2 x 8.8 MW (2 x 2,500 TR) heat pumps and associated distribution pumps and controls. Total system capacity when fully built out is 35.2 MW cooling (10,000 TR) and 45 MW heating (152 MMBtu/hr)
The north side heat pumps were placed into service in 2011, and south side will be installed in 2013.

During spring and fall, when cooling and heating is needed simultaneously, the heat pumps will work in heat recovery mode, meaning that waste heat from the chilled water system will be recovered directly via the heat pump to the heating system as opposed to warming up the Earth.

**Key design interface challenges/solutions**

**Technical**

The underground closed loop system will not require any antifreeze and will circulate only fresh water. In colder climates, similar systems require the use of an antifreeze such as propylene glycol, denatured alcohol, or methanol. Using water only allows for reduced heat transfer surfaces and less pumping energy.

Hot water supply temperature plays a major role in heat pump system design since the efficiency decreases with high supply temperature. For a campus consisting of a mix of new and old buildings it is imperative to find the optimal district system supply temperature. Either all buildings are retrofitted for a lower supply temperature or peaking boiler are installed within those buildings for use when needed. The figure above shows the relationship between district heating supply temperature and required supplemental heat capacity as a function of outside ambient temperature (OAT). For Ball State it was found that at a supply temperature of 65°C
(150°F) strikes an optimum between heat pump efficiency and required supplemental heat capacity at winter peak. At OAT warmer than -4°C (25°F), no supplemental heat is needed.

The availability of very large capacity heat pumps that have come to the USA market only in recent years made this project feasible and it would have been a different situation and substantially more difficult only ten years ago.

**Business**
The geothermal system was funded with assistance from federal and state governments. The U.S. Department of Energy provided a grant of $5 million under the American Recovery and Reinvestment Act. The Indiana General Assembly authorized nearly $45 million in state capital funding. Total capital investment required was $70 million (only $25 million incremental cost compared to the alternative of a new coal boiler).

The switch from fossil fuel steam generation to hot water ground source geoexchange is projected to save Ball State University $2 million in annual operating costs, resulting in a return on investment of about 8%. It will also shelter the university from U.S. EPA’s recently implemented Boiler MACT regulations for hazardous air pollutants.

The system’s implementation demonstrates that ground source heat pump technology can be used on a large-scale district distribution system.

*Thanks to Ball State University for photos, graphs and content contributions.*
9.2 Jena

Jena, Germany

Public utility provides heat and electricity using natural gas and biogas while preparing to further integrate renewables to meet Federal Government energy targets.

Sustainable Energy Technologies

Biogas and Hot Water Thermal Energy Storage

Organization and History

Jena’s first steam district heating system began operating in 1961 with a heating plant in North Jena (closed down in 1994). In 1968, a second steam network was built with a coal fired CHP plant in Winzeria and in 1993 the two networks were connected, allowing steam to be distributed from the CHP plant. In 1996 the primary energy source for the CHP plant was switched from coal to natural gas. In 1999 a heat transfer station was built in Burgauerstrasse allowing for heat transfer between steam and a high temperature hot water network. Biogas operated gas engine stations, in Zwätzen, were added to the system in 2008.

The public utilities company Energie Jena Pößneck GmbH (SWEJ) is the operator of the district heating network.

District Heating System

The district heating system has approximately 1,200 end users with a total connected heat load of 165 MW (563 MMBtu/hr) and an annual energy supply in 2012 of 410 GWh (1.4 million MMBtu).

The district heating network consists of 109 km (68 miles) hot water with the main part running at a variable supply temperature of 90-130°C (194-266°F) and 9 km (5.6 miles) steam network with a supply temperature of 240-300°C (464-572°F). Out of the total connected heat load only 40 MW (137 MMBtu/hr) are steam customers. The heat transfer station at Burgauerstrasse is used to transfer heat from steam to hot water. There are also two heat transfer stations within the hot water network to allow for a hydraulically separated secondary network (northernmost part) that runs with a lower supply temperature regime of 70-110°C (158-230°F).

The district heating production consists of one natural gas fired CHP plant (Winzeria) operated by E.ON and one biogas engine plant (Zwätzen) operated by Biogas Jena GmbH & Co. KG. The CHP plant has an electrical output of 197 MW and a thermal output capacity of 225 MW (768 MMBtu/hr). The biogas engine plant has an electrical output of 1.3 MW and a thermal output capacity of 1.4 MW (4.8 MMBtu/hr). In 2012 the heat production fuel mix was 98% natural gas and 2% biogas.
Sustainable Energy Integration

**Biogas**
A first step towards the integration of renewables took place in 2008 when two biogas operated gas engine stations (shown to the right) were integrated to the district system in Zwätzen.

For biogas production, raw materials from agriculture are used as substrates (44% corn, 6% grain, 31% manure, 19% whole plant silage / wilted silage) and the yearly substrate amount is 33,000 metric tonnes.

Heat recovered from the biogas engines feeds into the secondary network in the north, which is operated with a lower temperature regime and therefore allows for higher efficiency. The biogas plant supplies the base heat load in this network and the production is sufficient to cover all summer load requirements. The plant reaches an impressive Equivalent Full Load Hours (EFLH) of over 7,000 hours per year.

**Hot Water Thermal Energy Storage**
A hot water thermal energy storage was built next to the CHP plant in 2011. The storage is 42 m (138 ft.) high with a water volume of 13,000 m³ (3.4 million gallon) and able to store water with temperatures of up to 98°C (208°F). The thermal storage allows electricity and heat production to be decoupled, meaning hot water can be stored during low heat consumption periods while still producing electricity. As a result, this initiative allows production units to work in a more efficient way.

This storage could in the future also evolve to incorporate other renewable heat supplies such as solar thermal energy and wind electrical hot water preparation.

**Key design interface challenges/solutions**
In order to meet Germany's federally mandated targets for 2020 - 2050, renewables must have a larger share of the energy portfolio. Key challenges include:

- Financing and contractual obligations;
- High network temperatures;
- Regionally available renewable resources; and
- Transformation strategy.

At a first glance, the most logical step in Jena would be conversion of the existing CHP plant from natural gas to biogas or biomass. However, adding renewables from a separate feed would displace heat from the CHP plant, thereby reducing load hours and negatively affecting its economic performance. In any event, this conversion is not viable because the German Renewable Energy Act (EEG) limits the financing option of electricity generated from bio-fueled installations to 20 MW.
The district heating system’s high temperature currently limits the renewable options that can be incorporated. Low-temperature technologies such as low temperature geothermal, solar panel collectors, or waste heat from waste water cannot be supplied directly into the network under today’s conditions. Only the secondary network in the north is operated with lower temperatures; however the base load is already completely covered by the existing biogas plant and until the end of the financing for the plant (after 2025), no further renewable integration is acceptable since this would reduce the EFLH for the biogas plant.

The high temperatures also make renewable CHP solutions less economically attractive, due to the limited electrical efficiency at high temperatures, and EEG benefits are thereby reduced. The situation is further complicated by the fact that the high supply temperature is required by some customers for the operation of absorption chillers, which increases power and heat sales in summer.

An investigation of regionally available renewable resources included woody biomass, biogas and solar thermal energy. Woody biomass was not found to be feasible due to fuel supply limitations and emissions. Of the other three sources, GHG emissions were found to be only slightly reduced for the biogas and solar thermal energy scenarios; however, with the biogas scenario, a reduction of around 16% could be achieved (compared to the national mix).

The planned transformation strategy for integrating renewables into the district energy system in Jena focuses on small steps:

Step 1 (short-term)
Incorporation of a biogas engine plant feeding into the high temperature hot water network incurs the lowest specific heat generation cost for renewable options studied. With an additional 7.2 MW (24.6 MMBtu/hr) heat generation, the share of renewables will be 14% and GHG emissions will be reduced by 16%. Thus the target for renewable heat, defined by the Federal Government for 2020, will be achieved.

Step 2 (middle-term by 2025)
In order to increase the options for the integration of renewable energy, temperature reduction measures should be implemented in the next step (replacement of the steam network, temperature reduction in all or parts of the high temperature water networks).

Step 3 (long-term from 2025)
The heat purchase contract with E.ON ends in 2024 and EEG financing for the biogas plant will end. This allows for construction of further renewable units, e.g. biogas units or heat pumps with sewage waste heat usage.

Another important factor to consider in reaching mandated energy targets as a percentage of overall energy sources is that customer building heat efficiency is projected to increase over coming decades, resulting in a lower overall demand.

9.3 Greater Copenhagen Area District Heating

Copenhagen, Zealand/Amager, Denmark
Publically owned companies provide heat and electricity utilizing REWH sources.

Sustainable Energy Technologies

Organization and History
The heat distribution network in the Greater Copenhagen Area was initiated in 1903 in the municipality Frederiksberg and is today serves 19 municipalities. The system is divided into four integrated major supply areas operated by the four municipally-owned companies: Greater Copenhagen Utility (HOFOR), Metropolitan Copenhagen Heat Transmission Company (CTR), Vestegnens Cogeneration Society N/S (VEKS) and Vestforbrænding I/S (VF).

District Heating System
The Greater Copenhagen Area district heating system is one of the largest in the world, with approximately 500,000 end users and an annual heat supply of 9,600 GWh (32.7 million MMBtu) or about 20% of the total heat demand in Denmark.

HOFOR operates the largest distribution network in the area, situated in the municipality of Copenhagen including the city center. In this system alone the distribution network is currently 1,500 km (932 miles) long and provides more than 98% of the heating demand in the municipality of Copenhagen.

The Copenhagen system has developed in two tracks, partly in the form of a hot water-based system (90% of pipe length) and partly in the form of a steam-based system (10%). Conversion of the steam-based system to a hot water-based system is ongoing, and will be finished in 2025.

The district heating production consists of four CHP plants (AMV, AVV, HCV and SMV) owned by Vattenfall and DONG Energy, three waste incineration plants (AMF, VF and KARA), one sewage sludge incineration plant (RLF), and more than 30 peak load Heat Only Boiler (HOB)

plants. In 2012 the heat production was derived from following fuel sources: waste incineration (19%), coal (20%), biomass (31%), natural gas (23%), oil & diesel (6%), and geothermal (1%).

The system is highly flexible in terms of switching between production plants and fuels. It optimizes heat and electricity production in CHP plants on an hourly basis according to the lowest possible cost, including energy taxes and CO2-quota-costs. Supply temperatures are also optimized and vary, based on the weather forecast and customer building requirements, between 90-115˚C (194-239˚F) for the transmission pipelines and 80-95˚C (176-203˚F) for the distribution. The return temperature typically lies between 45-60˚C (113-140˚F).

Sustainable Energy Integration
CO2-neutral sources including biomass and organic municipal waste covered 45% of the 2012 annual heat production to HOFOR, CTR and VEKS, and are mainly produced at six locations as described below. Over and above these main plants there are also minor heat supplies from one geothermal demonstration plant and one solar thermal demonstration plant.

Biomass Combined Heat and Power
There are two CHP biomass plants connected to the system (AMV1 and AVV2) which together covers about 35% of the total heat demand for HOFOR, CTR and VEKS (2012). The biomass fuel fraction consists of 90% wood pellets and 10% straw (2012). These plants are owned and operated by two major energy producers (Vattenfall and DONG Energy), which requires a high level of strategic operation (see further discussion under key challenges). Key data on these plants is summarized below.

<table>
<thead>
<tr>
<th>Plant (Location)</th>
<th>Owner</th>
<th>Max Heat</th>
<th>Max Electricity</th>
<th>Annual Biomass (tons)</th>
<th>Year of Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMV1 (Amager)</td>
<td>Vattenfall</td>
<td>250 MW</td>
<td>80 MW</td>
<td>150,000</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(855 MMBtu/hr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVV2 (Avedøre)</td>
<td>DONG Energy</td>
<td>430 MW</td>
<td>140 MW</td>
<td>450,000</td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1,470 MMBtu/hr)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Max heat and electricity production shown in the table refers to simultaneously heat and electricity production. Total plant capacity is consequently the sum of the two.

Subsidies and energy taxes are the main drivers for the ongoing process of getting more biomass to the CHP plants. Subsidies are given to electricity production based on biomass. There is no tax on the heat produced, while heat production based on fossil fuels is taxed heavily.

Together with exchanges of CO2-quotas on the European emission market, the above mentioned subsidies and taxes makes CHP production based on biomass more economically feasible than CHP production based on fossil fuels.
As the first such plant in Denmark, AMV1 was also subject to a requirement of a minimum percentage of biomass-based CHP production.

**Thermal Storage**

Within the district heating system there are three hot water thermal storage facilities (steel tanks), two located at the AVV plant and one at the AMV plant. Storage volume is 3 x 24,000 m³ (3 x 6.3 million gallons), which corresponds to a capacity of 3 x 1,300 MWh (4,450 MMBtu) at a temperature difference of 45°C (81°F).

The heat storage facilities are used to optimize electricity and heat production from the CHP plants. Electricity is produced when the electricity spot price is high and heat can also be regulated when/if it deviates from the forecast of the heat demand.

**Municipal Solid Waste CHP and Sewage Sludge Incineration**

There are three CHP waste incineration plants (AMF, VF and KARA) and one sewage sludge incineration plant (RLF) connected to the system, which together cover approximately 49% of the total heat demand. The waste originates from both household and commercial activities with a typical fuel fraction of 67% organic and 33% plastic materials.

Waste incineration is considered CO2-neutral, apart from the plastic in the waste. The nationally recommended estimate for content of plastics in incinerated waste has doubled since the 1990s and affects Greater Copenhagen’s overall carbon emissions.

<table>
<thead>
<tr>
<th>Plant (Location)</th>
<th>Owner</th>
<th>Max Heat</th>
<th>Max Electricity</th>
<th>Annual Waste (ton)</th>
<th>Year of construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMF (Amager)</td>
<td>Municipalities</td>
<td>120 MW (410 MMBtu/hr)</td>
<td>29 MW</td>
<td>400,000</td>
<td>1991-2001</td>
</tr>
<tr>
<td>VF (Glostrup)</td>
<td>Municipalities</td>
<td>204 MW (695 MMBtu/hr)</td>
<td>31 MW</td>
<td>330,000</td>
<td>1976</td>
</tr>
<tr>
<td>KARA (Roskilde)</td>
<td>Municipalities</td>
<td>69 MW (235 MMBtu/hr)</td>
<td>12 MW</td>
<td>260,000</td>
<td>1999-2013</td>
</tr>
</tbody>
</table>

Note: Max heat and electricity production shown in the table refers to simultaneously heat and electricity production. Total plant capacity is consequently the sum of the two.
In 2017, AMF will be replaced with a new energy-efficient CHP waste incineration plant producing 63 MW electricity and 160 MW heat (545 MMBtu/hr). In addition to the technological merits, the architecture includes a roof-wide artificial ski slope open to the public (see picture).

The municipally owned sewage sludge incineration plant at Lynetten (RLF) was put into operation in 2011. It consists of a fluid-bed boiler together with a modern flue gas heat recovery and cleaning system. Heat production capacity is 3.8 MW (13 MMBtu/hr) used for drying the sludge and for district heating plus 2.8 MW (9.5 MMBtu/hr) flue gas condensation used only for district heating. The facility also produces biogas for city gas production.

Incineration of waste for heat is one component of a comprehensive waste management strategy in Copenhagen, where waste reduction, separation of waste, recycling, and incineration are the main elements. As a result, only 3% of waste in Copenhagen is deposited in landfills.

**Geothermal**

In 2005 a geothermal demonstration plant was established at the Amager CHP plant site. The geothermal plant uses the temperature of 73°C (163°F), at 2.6 km (1.6 miles) below the earth’s surface to produce heat. Three absorption machines, operated on steam from the CHP plant, raise the water temperature so that it can be utilized in the district heating network. The plant has an overall heat production capacity of 25 MW (85 MMBtu/hr), of which 13 MW (45 MMBtu/hr) is geothermal.

**Solar Thermal**

Greater Copenhagen Utility (HOFOR) invested 0.8 million EUR (2009) in a demonstration solar plant which includes 490 m2 (5,275 ft2) of solar panels, a heat storage system and a heat pump. The plant has a capacity of 0.28 MW (1.0 MMBtu/hr) and uses the heat pump to raise the water temperature from the solar panels or the storage tank before delivery to the hot water network.

**Key design interface challenges/solutions**

**Technical**

In a large system with several private companies providing heat to the district network and power to a free electrical market it becomes extremely important to optimize not only the production but also ensure a sound operation of the distribution network.

According to the competition rules in the electricity market, energy producers must not know of the production at each other’s plants. Therefore, to ensure overall system optimization and lowest possible heating costs HOFOR, CTR, and VEKS established a procedure for economic optimization of the daily heat production including a common load management unit, responsible for the following:
• Planning the next day of operation in collaboration with DONG Energy and Vattenfall.
• Adjusting the heating plans at 8am, 3pm and 10pm.
• Daily operation follow-up.
• Developing tools for joint optimization.
• Cooperation between control and back-office functions in each of the three companies.

Real time software simulations of the district heating network have also been incorporated to maximize production with REWH sources and minimize heat losses and pumping energy consumption to ensure lowest possible environmental impact. The simulation and control strategy includes:

• Hydraulic simulation of the system, allowing for faster detection of malfunctions and assessment of the potential for improvements in the district heating network.
• Supply temperature optimization, ensuring that the supply temperature is always as low as possible considering the accumulated energy in the net and changes needed as a result of the weather forecast.
• Remote monitoring of Energy Transfer Stations (ETS), allowing for detection of malfunctions and improvement of the customer performance, e.g. reduction of return temperature.

Business
Contracts between the non-profit-owned heat distribution network and privately-owned CHP plants allows for a split share of fuel cost savings arising from CHP production versus separate heat and electricity production (about 30/70 %). Those savings have financed the expansion of the heat distribution network in the Greater Copenhagen Area.

By law, Greater Copenhagen Utility (HOFOR) and the other heat distribution companies in Denmark are obliged to reduce the demand side energy consumption, and consequently energy saving services are offered to heat customers. The company also takes an active part in the analysis of sustainable heating options for new building stock that will meet the strictest requirements set out in the Danish Building regulation. Further incorporation of REWH fuels has a major role in facing future business challenges related to the reduced heat load demand.

The district heating system plays a major role in the municipal climate plan to achieve the 2015 goal of a CO2 emission reduction of 20% and the 2025 goal of being the world’s first CO2 neutral city.

The target for the Greater Copenhagen Utility is to obtain 100% share of renewable energy and waste incineration heat in the district heating system by 2025. Since incineration of plastic waste will emit CO2 equivalents, the aim is to divert all plastic waste from incineration towards various forms of recycling.

Thanks to CTR I/S for photos, graphs and content contributions.
9.4 Toronto Deep Lake Water Cooling

Toronto, Ontario, Canada
Private thermal utility provides deep lake water cooling.

Sustainable Energy Technologies
Deep lake water cooling.

Organization and History
Enwave Energy Corporation officially began in 2000 as a private, for-profit corporation jointly owned by the City of Toronto and the Ontario Municipal Employees Retirement Savings System. The predecessor company, Toronto District Heating Co was started in 1982 (but with roots that go back into the 1960’s) as a non-profit cooperative supplying steam only. The district cooling system became operational in 2004. Enwave was sold to Brookfield Asset management through a competitive sale process in 2012 at an enterprise value of $480 million.

District Cooling System
As of early 2013, the district cooling (DC) system has a growing customer base with 63 buildings connected and another 5 signed and slated for connection by 2015. It provides air-conditioning to residential, commercial, retail, institutional, and government buildings, and major sports facilities. The system has a potential to air condition 300,000 m² (3.2 million ft²) of office space in Toronto’s downtown financial district. The distribution system consists of over 14 km (8.7 miles) steel and high-density polyethylene pipes buried in tunnels below the City streets.

The DC plant capacity is 265 MW (75,000 TR) via the Deep Lake Water Cooling (DLWC) system and 47 MW (13,400 TR) of chiller capacity available for polishing, 2 x 16.5 MW (2 x 4,700 TR) steam driven centrifugal chillers and 2 x 7 MW (2 x 2,000 TR) electric driven centrifugal chillers. The plant includes stand-by power capability in 2 x 5.5 MW (11 MW total) steam turbine generators.

The company plans to expand the capacity of the system by introducing thermal storage. The expansion plans include refurbishing abandoned subterranean sand filters next to the City’s Island Filtration Plant that were once used to filter Toronto’s water. These cavernous chambers will be cleared of sand, lined and used as large thermal storage tanks providing an additional 560 MWh (160,000 TR-hrs) of peak cooling supply, 63 MW (18,000 TR) x 8 hours/day. The expansion also includes an additional 28 MW (7,900 TR) of new chiller capacity at the John Street Pumping Station. When completed in 2016, the expansion will increase system capacity to 352 MW (100,000 TR).

Sustainable Energy Integration
Water drawn from Lake Ontario is pumped to the Island filtration plant through three high density polyethylene (HDPE) 1600 mm (63 inch) diameter intake pipes extending 5.6 km (3.5 miles) into the lake. The pipes follow the natural slope of the lake and settle on the lakebed at a
depth of approximately 85 m (270 ft). The use of three pipes to draw water from the lake is a safeguard to ensure input from two pipes if one should be out of service for any reason.

The treated lake water, at about 4°C (39°F), is fed from the Island filtration plant to Enwave’s Energy Transfer Station (ETS) where it is used to cool down the DC system return water and then continues on to the City of Toronto potable water distribution system. The closed loop DC system uses only the coldness from the lake water (not the actual water), and physical separation between the two systems is maintained via 36 heat exchangers.

During peak demands the DC system supply temperature requirement is 3°C (37°F); to achieve this steam driven centrifugal chillers operate in series with the heat exchangers on the DC side.

With DLWC electricity consumption is reduced 90% compared to conventional in-building systems. This frees up over 60 MW of electricity for other consumers on the electrical grid. Additionally 79,000 tonnes (87,000 tons) of CO2, 145 tonnes (160 tons) of NOx, and 318 tonnes (350 tons) of SOx are not emitted into the atmosphere. Water consumption from cooling tower evaporation is reduced as well, saving some 700,000 m3 per year (185 million gal.).

The system has also substantially improved Toronto’s summer drinking water, which would otherwise come from the warmer and shallower waters closer inshore, which resulted in taste and odor problems during warmer weather.

**Key design interface challenges/solutions**

**Technical**

Enwave experienced some technical challenges in the design and deployment of the project. For example, they carried out a lake water temperature monitoring program and found that the existing literature did not represent the actual temperature regime in the lake. As a result the intakes had to be lengthened from 2.7 km (1.7 miles) to 5.6 km (3.5 miles) to go beyond the shoreline effects that were picked up in the monitoring program.

**Business**

Enwave needed to dispel misconceptions about district energy, DLWC project viability, and costs for converting from in-building cooling systems in order to get customers to sign up. For many customers, agreeing to long-term contracts (some nearly 20 years) was a challenge, despite the many environmental and financial benefits.

A key message conveyed to potential customers was that the project offered long-term price stability (insulation from price hikes for electricity or gas) and reduced maintenance costs. Enwave addressed its customers’ concerns directly by presenting a sound business case that offered a detailed financial analysis over the entire life of the project.

Other messages that helped persuade customers to sign up were energy and maintenance costs savings and worry-free operations, as well as the realization that a chiller purchase is really a 25 year commitment since chillers last on average almost that long according to ASHRAE.
Careful consideration should be given to the expected start date of a project and associated increases in material costs, as well as access to skilled labor not only for construction but also for the operation and maintenance of a plant.

The total cost of the project was C$250 million. Financial support for advanced engineering work was provided by the Department of Natural Resources Canada in the form of a grant of $1 million (half repayable) and additional private equity from shareholders, for a total feasibility and engineering cost of $3.5 million. The Federation of Canadian Municipalities provided a capital works loan from the Green Municipal Fund of $10 million at market rates.

*Thanks to Enwave Energy Corporation for photos and content contributions.*
9.5 Stockholm District Cooling

Stockholm, Sweden
Utility provides district cooling using renewable sources including sea water cooling, waste cooling from heat pumps and thermal storage (aquifer and underground cold water).

Sustainable Energy Technologies
Sea water cooling, waste cooling from heat pumps and thermal storage (aquifer and underground cold water).

Organization and History
Fortum Värme operates as a subsidiary of Fortum Power and Heat AB. Fortum owns 90.1% and the municipality of Stockholm 9.9%. The company generates and distributes electricity, heating, cooling and gas. The company was founded in 1919 and is headquartered in Stockholm, Sweden. The seawater-based district cooling scheme was established in 1994 and has continuously grown since then.

District Cooling System
Stockholm boasts one of the largest district cooling systems in the world with a distribution network which is currently 204 km (127 miles) long. More than 600 customers, with 7 million m² (75 million ft²) of commercial area including offices, hospitals and universities, are supplied. Peak demand is currently 220 MW (62,500 TR) with an annual supply of 350 GWh (100 million TR-hrs). The system has been designed for 10 – 16 barg (150 – 225 psig) with a supply and return temperature of 6/16°C (43/61°F).

Cold water from the sea bottom is used as the base load production. During wintertime the energy in the district cooling system is used as a heat source for heat pumps to produce district heating (otherwise the amount of free cooling would have been greater). Conventional chillers are used when additional production is required during summertime peak hours. To minimize the use of peak production and to extend the peak production capacity, Fortum Värme utilizes a combination of a seasonal cold storage (aquifer storage in Brunkebergsåsen) and a short-term storage (underground storage in Hornsberg).
Sustainable Energy Integration
In 2012 district cooling production was derived from: sea water cooling (22%), waste cooling (35%), heat pump cooling (40%) and conventional chillers (3%). Annual CO2 emissions are reduced by about 50,000 metric ton as compared with 100% conventional chillers, and the amount of harmful refrigerants has been reduced with more than 70 tonnes (77 tons).

Sea water cooling and heat pumps at Värtaverket
The sea water intake at Värtaverket is used either directly as a “free cooling” resource or in combination with heat pumps that simultaneously deliver heat to the district heating system. The heat pump facility (Ropsten) is Europe’s largest heat pump plant and consists of ten heat pumps.

Two sea water inlets feed the plant, one immediately located at the shore and one at the sea bottom 20 m (65 ft.) below the surface and 170 m (560 ft.) off shore. Both intake pipes are wooden tube with a diameter of 3 m (10 ft.). Stockholm’s situation is unique because sufficiently cold water is available at very shallow depths almost all year round. The fresh water has lower density than the salt water, so the fresh water ‘floats’ on top of the salt water on its way through the archipelago and out into the Baltic sea. The counter current carries cold sea-bottom water to the district cooling system.

Six titanium heat exchangers provide a total capacity of 70 MW (20,000 TR). After passing the heat exchangers the water is either returned to the heat pumps or is released back into the sea.

Total heat pump capacity in Ropsten is 240 MW heat (820 MMBtu/hr) and 160 MW cooling (45,500 TR) at an evaporating temperature of −3°C (26.5°F) and condensing temperature of +82°C (190°F). All heat pumps have two stage turbo compressors, tube in shell condensers and open spray evaporators.

Annual cooling supply from Värtaverket is approximately 220 GWh (62 million TR-hrs) with 35% originating from deep water cooling and 65% from heat pump cooling.

Wastewater utilization in Hammarbyverket
At Hammarbyverket heat pumps use the energy in treated wastewater from the Henriksdals water treatment plants and discharge the heat the district heating network. This process results in cold wastewater which is then used in the district cooling network via heat exchangers. Finally, electrical power is generated in a turbine as the wastewater flows to a lower elevation.

Hammarbyverket is the world’s largest heat pump facility where district heating and cooling are simultaneously produced from treated wastewater. The plant consists of seven heat pumps with a total installed capacity of 240 MW heat (820 MMBtu/hr) and 62 MW cooling (17,500 TR) connected to the district cooling network. The plant is widely considered as an excellent example of optimum utilization of community resources. Annual cooling supply from Hammarbyverket is approximately 50 GWh (14 million TR-hrs).

Seawater cooling at Beckholmen
An additional source of deep water cooling is currently under construction and is expected to be fully operational in 2016. Cold sea water will be pumped from Saltsjön at 30 meters depth (100 ft.) to a new underground Energy Transfer Station located at Beckholmen. The water, once
passed through the heat exchangers, will be discharged back to the sea at a depth of 15 m (50 ft.).

Maximum cooling production capacity will be 90 MW (25,500 TR), with an annual reduction of CO2 emissions estimated to 20,000 metric tons compared to conventional chillers.

Aquifer Storage in Brunkebergsåsen
The aquifer storage in Brunkebergsåsen is a seasonal storage added to the system in 1998. It allows Fortum Värme to store cold water from the sea in an underground aquifer during winter and then use the cold aquifer water for district cooling during summer. The brackish seawater never comes into direct contact with either the aquifer water or the district cooling water but rather is separated from them using plate and frame heat exchangers. The storage is designed for a capacity of 25 MW (7,100 TR) at a working temperature of 4 - 14°C (39 - 57°F) and flow rate of 2,150 m³/h (9,500 gpm).

Underground storage in Hornsberg
The underground storage in Hornsberg was added to the system in 2010 along with new connecting pipes in 2012 (see photo). Excess cooling generation available during low demand periods is used to charge the energy storage in order to increase capacity during high demand periods.

The storage contains 50,000 m³ (13 million gal.) water and has a thermal storage capacity of 80 MW (22,500 TR).

It has been estimated that the storage decreases annual CO2 emissions by 30,000 metric tons.

Key design interface challenges/solutions

Technical
After launching district cooling in Stockholm the customer growth was much faster than expected, which actually led to a temporary stop in new customer contracts in 2005 due to the lack of production capacity. The situation was mainly resolved by connecting several smaller and temporary DC systems.

Business
New restrictions in Sweden placed on chlorofluorocarbon (CFC) refrigerants were the key driver in getting the scheme underway.

When launching a new product, the paramount achievement is to create confidence among customers. One explanation for the success in marketing district cooling in Stockholm can undoubtedly related to the fact that for over 50 years property owners were used to buying heat from large district heating systems with a reliability level exceeding 99.7%.

Following were some important business related decisions incorporated by Fortum Värme when introducing the district cooling system:
Pricing according to the alternative cost principle;
Individual contracts;
One building - one contract;
Long-term contracts to give security to customers;
Regulation of pricing based on the consumer price index; and
Pricing structure which included a connection fee (with an option of a fixed annual fee) and ongoing charges for capacity and energy.

A connection fee is always advantageous for the cash flow but Fortum Värme found it had a negative impact on prices at renegotiations. Therefore, in 2005, Fortum Värme switched to a fixed annual fee, capacity charge and energy charge for all new contracts and renegotiations.

Fortum Värme has also learned that economic risks associated with customers' behavior such as low delta T and over/underestimating the load demand can be successfully reduced through the price structure.

Thanks to AB Fortum Värme samägt med Stockholm stad for photos, graphs and content contributions.
9.6 Solar Village Wiggenhausen-South

Friedrichshafen, Germany
Public service company provides solar-assisted district heating system with seasonal hot water storage.

Sustainable Energy Technologies
Solar thermal, long term (seasonal) hot water thermal energy storage.

Organization and History
Technische Werke Friedrichshafen GmbH (TWF) is a public service limited company, established in 1981, providing energy and water supply, transport and other services.

District Energy System
The city of Friedrichshafen has one of the first German solar-assisted district heating systems, which went into operation in 1996. TWF is the owner and operator and has also assumed the builder’s and operator’s risk.

District Heating
The small scale district heating system supplies a residential estate with 570 housing units. Through solar collectors installed on the roofs of the multi-story housing complex, solar heat is captured during the summer months and fed into a long-term/seasonal hot water storage tank in the heating plant via a separate solar-heat distribution network and a heat exchanger. The district heating plant also includes a condensing gas boiler for off-season requirements.

Sustainable Energy Integration
The achieved annual solar fraction (based on total heat demand) varies between 20 - 30 %. The goal was to cover almost 50% of the total heat demand for the space heating and hot water supply requirements of the buildings with solar energy. This has not yet been realized mainly due to high return temperatures in the district heating system (see key design interface challenges below).
Solar Thermal
Over 5,600 m² (60,000 ft²) of flat plate solar thermal collectors have been installed on the roofs of the single family houses and multifamily buildings. Some of the collectors are on elevated mountings on the roof, while others are integrated into the roof. The costs, including final assembly of the collector arrays, ranged from about 175 - 235 Euro/m² (23 – 30 $/ft²), depending on the model of collector.

Long-term Thermal Energy Storage
The long-term or seasonal thermal energy storage tank is a cylindrical reinforced concrete non-pressurized tank with a water volume of 12,000 m³ (3.2 million gallons). To reduce vapor diffusion and heat loss the tank has a stainless steel liner and mineral wool insulation. The tank is also entirely buried in soil.

Charging of the storage tank mainly occurs from May to August, discharging in the autumn months. Approximately 20 % of the heat delivered by the solar collectors is used directly for preheating the district heating system.

The storage tank is designed for a solar collector area of 5,600 m² (60,000 ft²) and a maximum temperature of 95°C (203°F). Until 2004 the maximum temperature was between 80 - 85°C (175 - 185°F) with a vertical stratification of 20 - 30°C (11 - 17°F).
Key design interface challenges/solutions

Technical

One major reason for not reaching higher solar fractions was the high district system return temperature of around 50°C (122°F); in contrast the design was for less than 40°C (104°F). The high return temperature also limits the thermal storage, allowing only about 70% of original heat capacity to be usable.

Despite many efforts to reduce the return temperatures no success has been achieved yet. The main responsibility for improving return temperatures is with the building owners, who are housing companies who do not show any interest in improving their buildings due to the extra capital cost.

In addition, in the early years of operation heat losses in the thermal storage tank were much higher than expected. This was not only because quasi-steady-state conditions in the ground had not been reached but also due to wet thermal insulation caused by flooding of ground water. Another reason for not reaching higher solar fractions is that the heat consumption of the buildings has been about 10% higher than expected.

The expected 100% coverage of heat supply from the solar installation during the summer and early autumn months has not been achieved. This may be related to control issues.

Business

The capital costs for the first section of the solar-district-heating system amounted to about 3 million Euro ($4.2 million). For 280 completed housing units, this means an outlay of about 10,000 Euro/unit ($14,000/unit). Total annual O&M costs of 90,000 Euros ($125,000) and an annual heat output of about 2,000 MWh (6,800 MMBtu), resulting in a heat price of about 45 Euro/MWh (18.5 $/MMBtu).
The Federal government subsidized the construction of the long-term storage and the district heating system with a total of 53% of total costs. Other important supporters were the clients, with construction-cost subsidies of 24% of the total costs for connecting to the district heating system and the solar energy facility. The solar collectors of the first section were subsidized by the State of Baden-Württemberg with 9% of the total costs.

*Thanks to TWF for photos, graphs and content contributions.*
9.7  Húsavík Geothermal Power Plant

Húsavík, Iceland
Private thermal utility provides heating and electricity using geothermal water.

Sustainable Energy Technologies
Geothermal, combined heat and power, thermal energy storage.

Organization and History
Húsavík Energy is an Icelandic company engaged in district heating and electricity production by means of geothermal water with combined heat and power (CHP).

District Energy System

District Heating
Initially the district heating system used 100°C (212°F) water from hot water springs at Hveravellir, 20 km (12 miles) south of Husavik to supply hot water to all housing. The chemical composition of the water in the springs allowed direct use without any need for heat exchangers.

This scheme has evolved into extracting well water near 120°C (248°F) and using the geothermal fluid to generate electricity by cooling it down to 80°C (175°F) through a CHP unit. The water is then used for district heating, snowmelting, industrial processes, greenhouses and fish-farming. Much emphasis was assigned to obtaining flexibility within the system.

Sustainable Energy Integration

Geothermal
Geothermal water with a temperature of 115-128°C (240-262°F) from the production wells is delivered through a pre-insulated DN400 (16 inch) steel pipe to the Energy Center. Once the geothermal water arrives at the Energy Center it is first utilized (via heat exchangers) for applications requiring temperatures higher than 115°C (240°F) such as electricity production in the CHP plant and various industries. Once the temperature has fallen to 80°C (175°F) through
these processes it is used in the district heating distribution system for space heating, industrial purposes, and snow melting.

**District Heating and Thermal Storage**

The 80°C (175°F) byproduct from the CHP plant is initially sent through the hot water storage tank before entering the hot water distribution system for space heating, tap water and industry use. The outlet temperature after heating the buildings is typically 35°C (95°F). After heating the buildings a part of the water is used for snow melting purposes, which further reduces the return temperature to 15°C (60°F). All geothermal water is at last sent to the sewer system.

**Combined Heat and Power**

The CHP plant is a binary cycle power plant which operates based on the Kalina cycle. This concept has never been applied to geothermal prior to its installation at Husavik. The main difference between the Kalina technique and a traditional binary fluid system lies in the type of transfer medium used in the closed electricity production cycle. The Kalina cycle uses a water and ammonia mixture (NH₃ – H₂O), while the traditional organic rankine cycle (ORC) uses pentane or a similar chemical. Pentane boils at a constant temperature, while temperatures vary in a boiling water-ammonia mixture. This property of the transfer medium was used to increase production efficiency in Húsavik.
The electrical power generation has a capacity of approximately 2 MW and can meet nearly three quarters of Husavik’s current electricity demand. Warm condenser cooling water (fresh water) from the CHP plant is used for a man-made bathing lagoon and/or fish farming.

**Key design interface challenges/solutions**

**Technical**

Initially the 18 km transition pipeline from Hveravellir to Húsavik consisted of an uninsulated, subsurface, asbestos-reinforced cement pipe. The elevation difference between Húsavik and Hveravellir is around 100 m (330 ft). Húsavik is the lower area, so water was distributed by means of gravity at atmospheric pressure. First the water had to boil off down to 100°C (212°F) and then, due to transition piping heat losses, the temperature was reduced further by 15°C (27°F) before arriving in Húsavik at a temperature of 85°C (185°F).

In the new concept a preinsulated steel pipe was installed which minimizes heat losses and allows the transition pipeline to be pressurized. Due to the higher pressure, maximum temperature is now 128°C (262°F) and temperature losses are reduced to about 3°C (6°F). The transmission pipeline has proven to function well, aside from small initial problems regarding deaeration of the geothermal water.

Quite a number of problems came up initially regarding the Kalina power plant. Issues that had to be resolved were mainly related to the steam separator, condenser and turbine interior design. Fluid and steam was not 100% separated, with the consequence that fluid was sent into the turbine and damaged the turbine blades. There were also corrosion issues and the turbine blades were changed from 13% chromium steel to titanium.

**Business**

In Húsavik the market for electricity has been a very stable and safe market while the heat demand from buildings and the industrial sector was not enough to fully utilize the hot water available. It was therefore decided to build a CHP together with a flexible utilization of the heat, enabling the system to utilize the energy as efficiently as possible under varying conditions.

The total capital investments in the Húsavik Geothermal Development have been 12 million EUR, of which 8 million EUR was spent on renewing the district heating system and 4 million EUR on the CHP plant. The Húsavik municipality financed about 92% thereof, other project partners 2% and the remainder came from the European Union.

*Thanks to Húsavik Energy for photos, graphs and content contributions.*
9.8 Munkegärde District Heating Plant

Kungälv, Sweden
Kungälv Energi AB provides heating using local waste wood and solar thermal collectors.

Sustainable Energy Technologies
Biomass, solar thermal and hot water thermal energy storage.

Organization and History
Kungälv Energi AB was established in 1992. The Munkegärde district heating plant was officially started in 1996 after the town administration decided to construct a biomass heating plant and facilities for thermal solar collectors.

District Energy System
District Heating
The hot water district heating system currently serves close to 200 single-family homes and 200 other buildings, including schools, industrial buildings, and apartments, providing about 50% of the energy required in the city of Kungälv for space heating and domestic hot water.

The heat supplied by the district heating plant is approximately 84 GWh (285,000 MMBtu) per year, of which 67 GWh (220,000 MMBtu) is from wood chips, 3.5 GWh (12,000 MMBtu) from solar energy and the remainder from oil.

Sustainable Energy Integration
Biomass Plant
The biomass facility replaced 38 local oil-fired systems and established a centralized heat supply system. The plant includes a 13 MW (44.5 MMBtu/hr) wood-chip-fired boiler with flue gas exhaust recovery, two 12 MW (41 MMBtu/hr) oil-fired boilers and a 1,000 m3 (265,000 gal.) thermal energy storage tank. Wood chips are produced from forestry residues and the ash from the plant is scattered in the surrounding forests.

Solar Thermal
The solar plant was installed in 2000 (at that time the world’s largest) and consists of 800 flat type solar collectors of 12.5 m2 (135 ft2) each, totaling 10,000 m2 (110,000 ft2), and installed in rows on simple concrete foundations.
The goal of the solar facility was to increase the capacity of the local district heat system and to contribute to implementing Kungälv’s energy plan. A further decisive motivation was public relations – creating a demonstration project for innovative technologies (~8% improved efficiency due to antireflection coating of the glass and other design improvements).

The collector system is controlled to meet the district heating supply temperature, which is about 70°C (158°F) in the summer. The heat is passed to the district heating network through a heat exchanger. When the solar output exceeds the load requirement, excess heat is stored in the thermal storage tank.

The solar collectors generate around 3.5 GWh (12,000 MMBtu) of solar heat annually and thereby decrease CO2 emissions by 1,000 ton/year. Oil consumption has fallen by 440 m3 (115,000 gal.) per year and emissions of nitrogen oxides and sulphur dioxides have decreased.

The total investment in year 2000 was about 2.3 million Euros (US$1.9 million) excluding cost of the land. It was funded together with the Swedish government and the European Union (~35%).

Key design interface challenges/solutions
The facility was fully operational between 2001 and 2007 without any significant problems. In 2007 it was discovered that some of the district heating pipes were cracked due to stress load. This was a result of poor installation where pipes had been bent on site by an excavator. Despite extensive reparations the system could no longer operate and had to be drained and turned off in 2009. In 2010 it was also discovered that all solar panels had been damaged during the operation with leaking pipes and had to be replaced.

Reparation cost for all 800 panels was estimated to 1.5 million Euros ($1.2 million). In 2012 one third of all panels were exchanged (financed 50% by the county and 50% by Kungälv Energi).

Thanks to Kungälv Energi AB for photos and content contributions.
9.9 Lindesberg District System

Lindesberg, Sweden
Public-private partnership provides district hot water from industrial waste heat and other sources.

Sustainable Energy Technologies
Industrial waste heat recovery, biomass, combined heat and power.

Organization and History
The hot water district heating system was established by the Linde Energi electricity utility in the 1980s. The waste heat concept was promoted by a strong mutual co-operation between the companies involved. It started operation in 1998 and has resulted in an annual reduction of CO2 emissions of about 16,000 tonnes (17,600 tons).

District Heating System
The characteristics of the district heating system are summarized in the load duration figure below. The supply temperature varies based on outside ambient temperature and ranges between 75-110°C (167-230°F). A typical return temperature is 45°C (113°F).

District heating is delivered to approximately 4,500 apartments, schools, factories and public buildings. Approximately 40 to 60 properties have been connected to the district heating network each year.

Sustainable Energy Integration
The waste heat source, limited in temperature to 86°C (187°F), is available throughout the year. The waste heat is based on low temperature coolant water outlet in series with a boiler flue gas recovery. For the coldest 3,500 hours/year the waste heat is tempered with an industrial boiler using primarily biomass fuel. The peak load is supplied by oil boilers.
The waste heat plant was installed in 1998. The estimated cost was 150 million Swedish Krona (MSEK) (US$18 million), but actual costs were lower due to successful procurement of distribution pipes and contractors. The investment was also supported by public grants of 10% of the total investment. Operation costs are low and mainly related to distribution.

**Key design interface challenges/solutions**

To maximize annual waste heat recovery it is essential to maintain a low temperature heat sink in general and preferably also a gradual recovery sequence by recovering the lowest temperature sources first (exergy analysis). A proper control and monitoring system is essential.

From a business perspective it is important that all actors have access to the energy system in an economically transparent way, with visibility relative to:

- Investment;
- Net operational cost reduction in regard to possible alternative fuel costs;
- Profit by risk exposure for each actor involved;
- Heat supply value (pricing) in regard to delivery commitment; and
- Confidence in business ethics

It is important to thoroughly address business risk analysis when district heating systems integrate external heat sources. The analysis should address short term consequences of sudden shut down as well as long term means to secure/finance alternative base load supply.

The expansion of district heating in residential areas were from the beginning somewhat less than planned because the homeowners' association in Lindesberg discouraged their members from connecting to the system. It turned out that the association had a commission on the oil that members bought. Today the situation is however different.

The companies involved in the development of the waste heat concept were awarded the national Eco Prize in 1999.

_Thanks to Linde Energi AB for photos, graphs and content contributions._
9.10 Norrköping Multiple Energy Source System

Norrköping, Sweden

Public-private partnership using biogas, CHP and municipal waste to heat buildings and industry and to supply transportation fuel.

Sustainable Energy Technologies
- CHP based on waste incineration and biomass.
- Transit distribution of district heating to neighbor city.
- External steam supply for an industrial ethanol plant.
- Biogas produced from sludge in the municipal wastewater treatment plant.
- Biogas produced from stillage from the ethanol plant and various kinds of crops.
- District cooling based on surface water resource.

Organization and History
The hot water district heating system was established by the municipality of Norrköping in 1951. In the 1990s the energy utility was sold out in stages to the private energy estate E.ON. The multiple energy system has gradually developed from well-defined independent business concepts for market mature products. This cautious approach has proven to be commercial sustainable. The ethanol plant was erected in 2001 and enlarged in a second step in 2008. The extensive biogas system and processing of vehicle fuels started in 2010.

District Energy System
The characteristics of the district heating system are summarized in the load duration figure. The supply temperature varies based on the outside ambient temperature and ranges between 75-110°C (167-230°F). A typical return temperature is 45°C (113°F). The load duration figure excludes power generation.

---

**Norrköping district heating system**

350 MW / 1000 GWh/year

- Fossil fuels 100 GWh/y
- CHP biomass 400 GWh/y
- CHP waste incineration 500 GWh/y
The district cooling system, established in 1997, is of minor size, comprising an annual turnover of 10 GWh/year (2.8 million ton-hrs). The distribution net is 6 km (3.7 miles) and supplies 30 commercial buildings.

**Sustainable Energy Integration**

The CHP fuel sources are predominantly renewable and include woodchips, wood waste, tires and household waste. 15% of the output is delivered as electricity, 55% as heat to the hot water district heating grid and the remaining 30% as process steam to a nearby ethanol plant. About 40 GWh/year (140,000 MMBtu) of district heating is distributed to a neighboring city. This was a sustainable environmentally friendly alternative to replacing outdated and ineffective baseload boilers; peaking boilers are still operated locally.

The biogas concept is part of a national sustainable program to transform from fossil to green fuels in the transportation sector. The basis for this program is to use waste of organic origin as a profitable resource instead of an economic burden. Of importance is the presence of local organic substrate and long-term rules for a stable end-user demand.

**Key design interface challenges/solutions**

From a technical aspect there were no extraordinary challenges because common system solutions and traditional technologies were used. However, business design is always of great importance with multiple linked energy systems. Confidence in business ethics is essential to find reasonable approaches to pricing, risk-taking and adequate profitability. Public support is essential in the transportation sector to promote technology and end-user demand of renewable fuels.

*Thanks to E.ON for photos, graphs and content contributions.*
9.11 Östergötland Municipal Waste Management

Cities of Finspång, Norrköping and Linköping in Östergötland, Sweden
Cities provide district heating and vehicle fuel using municipal solid waste as a renewable source.

Sustainable Energy Technologies
Municipal solid waste and biogas.

Organization and History
Waste to energy in Sweden
Sweden has worked for decades to convert municipal waste from a societal burden to an environmentally friendly economic resource. As a driving force for the conversion, landfilling fees have been gradually imposed. The figure below shows how Sweden has successfully managed to convert household waste management from landfill to sustainable recovery between the years 1975 to 2012.

The general order of priority is to minimize waste generation, reuse and/or recycle sustainable resources, and lastly dispose in landfills.

Municipalities are responsible for taking care of household waste management. Other waste sources are handled by the operator, which could be public or private actors. Landfilling of combustible and organic materials is now prohibited.
The conversion of the waste handling sector is a national commitment and has been carried out on a nationwide basis. The utilization of waste as an energy resource has also been part of the Swedish program to cost-effectively and sustainably switch the district heating sector from oil to renewable fuels. The Swedish district heating sector currently produces 60 TWh heat per year (0.2 million MMBtu), with 20% derived from municipal waste fuels and another 5% from industrial waste. The fossil fuel part is currently about 15% while in 1970 the equivalent fossil fuel share was 98%.

**County Östergötland**

The solid waste-based energy recovery in Östergötland consists of three independent hot water district heating systems located in the cities of Finspång, Norrköping and Linköping, with a combined population base of 0.5 million inhabitants. The first solid waste combustion plant was built in Linköping in 1980, followed by Finspång and Norrköping in the 2000s. As a complement to the combustion plants, anaerobic digestion facilities for biogas production were built in Linköping (1995) and Norrköping (2010). Biogas is used as an alternative vehicle fuel to contracted and public filling stations.

**District Energy System**

The range in size, waste treatment and technical system solution is substantial between the three cities. To some extent processing plants for biogas are also integrated with the district heating systems for supply of heat needed for homogenization of the raw material and purification of biogas.

**Solid waste combustion**

The solid waste combustion system includes both small- and large-scale plants in the range of 10 -100 MW (35 – 350 MMBtu/hr) and 100-1,000 GWh/year (0.35 – 3.5 million MMBtu). The waste material includes both sorted and unsorted fractions from household and/or commercial operations, and is burned in grate boilers or fluidized bed boilers. The two biggest plants are waste-based CHP, while the smallest produces heat only.

Waste material streams per plant are within the range of 30,000 to 400,000 metric tons per year, with the share from household ranging between 35-90%. The fraction of heat and electricity produced from waste sources is essential for each plant and represents approximately half of the total fuel balance. Most of the waste originates from local resources but also from trade and transport with national and/or imported waste as a result of a free market and to some extent also due to overcapacity.

The municipality's processing fee for waste becomes an income for the district heating company, and together with the revenue from heat sales supports a stable and profitable waste-based district heating business. Due to the ongoing plant capacity expansion in Sweden, processing fees have been gradually reduced over several years. However, as a result of the upcoming landfill ban within the European Union, further waste market growth is expected, with a temporary advantage for Sweden to utilize imported waste in existing plants.

**Solid waste biological treatment**

There are also biogas plants utilizing a biological waste stream that originates mainly from regional industries (65,000 metric tons per year in Östergötland). Biogas is used for vehicle

139
fuel, which has become a market with the highest alternative payback for the gas and in many cases also the best environmental potential for replacing fossil fuels. As for district heating, the main economic driver for biogas production is the processing fee in combination with the compensation for gas sales. The byproduct sludge also has an economic value as a certified land fertilizer. After a weak economic period of almost a decade, the profitability is now gradually improving for biogas.

Biogas plants in Östergötland have a thermal output equivalent to 30 MW (100 MMBtu/hr), resulting in a maximum gas production corresponding to 250 GWh/year (0.85 million MMBtu). Today’s production is just under 50% of the capacity. About half of the current production is used in public transport. All urban buses more than 100 units are driven by biogas. The second half is used by the private/public market through 10 filling stations. Overall the current biogas production replaces about 12,000 m3/year (3.2 million gal.) of liquid fossil fuels.

**Waste water treatment**

Waste water treatment plants in Linköping and Norrköping have historically burned raw gas from the anaerobic sludge digestion. However, now the anaerobic sludge digestion is used for commercial production of biogas.

**Sustainable Energy Integration**

In a view of sustainability, the Swedish model to recover combustible waste fractions as a district heating resource is well established. The combustion plants are normally located within or in close proximity to major cities, normally beyond the prevailing wind direction. Environmental permits prescribe and monitor environmental impacts.

Several decades ago there were objections to the potential impact of waste plant emissions on humans and nature. Over the years, these risks have been minimized through stringent quality control of waste fractions, improved plant performance and stricter emission requirements. The challenges/concerns today are more about increases in waste generation in general and the additional emissions arising from transportation and the disposal of combustion residuals.

Strategically, the local biogas developments in Östergötland connect to a national program that supports the utilization of biological waste, e.g. developing solutions to convert from fossil fuel dependency for transportation. In fact, transportation is the primary remaining sector to be prioritized for conversion to a renewable fuel basis. In the build-up of the market and infrastructure for renewable energy systems, various governmental investment programs and municipal procurement of renewable services (biogas-based public transportation services) played a vital role. These environmental policy instruments facilitate a sustainable transformation of the Swedish energy system.

**Key design interface challenges / solutions**

The expansion of solid waste combustion for district heating and biogas production started as a way to manage waste residuals in an environmentally friendly manner without any significant costs. Östergötland was one of the first regions in Sweden to implement new technology for waste incineration and controlled production of biogas for the transportation sector. At the time, there were basically no available technical solutions on the market and hardly any experience

worldwide. New technologies were established in a small manageable scale to gradually learn and to make the right decisions for future ongoing efforts.

Locally sourced solid waste was initially burned in hot water grate boilers connected to the district energy system. Over the years, technology solutions have been refined with quality-assured waste fractions, new combustion technologies and combined heat and power. Business development for trading in solid waste has also significantly evolved over the years.

Controlled and commercial biogas production must ensure upstream supply of waste substrate and downstream demand for biogas. Expansion of biogas production in Linköping was based on a co-funded facility for primary digestion of slaughterhouse waste. Business set-up ensured a reliable supply of pumpable substrate. The demand for vehicle fuel was secured by the introduction of gas buses in the municipal public transportation system. Today, a broader base of substrate is used all the way from foodservice and household waste to quality-assured waste fractions in the form of distiller’s waste and green biomass.

Waste facilities in Östergötland are described in the literature as an excellent example of an environmentally friendly way of forming a sustainable energy system. The facilities are regularly visited by people from all over the world.

*Thanks to Östergötland Municipal Waste for photos, graphs and content contributions.*
9.12 Princeton University

Princeton, New Jersey, USA
University provides heating, cooling and electricity using CHP, biodiesel, solar and thermal storage.

Sustainable Energy Technologies
CHP, biodiesel, solar photovoltaic, chilled water thermal energy storage, and flue gas heat recovery.

Organization and History
Princeton University is one of the nation’s oldest academic institutions (chartered in 1746). It has today expanded to include 180 buildings within a campus area of 2 km\(^2\) (500 acres).

In the mid-1980’s Princeton’s Facilities Department began to evaluate options to replace its aging central steam plant. Combined heat and power (CHP) was studied because the local electric utility had some of the highest rates in the country.

In 2007, the university created a sustainability plan to conserve natural resources and reduce carbon-dioxide emissions to their 1990 levels by 2020 without the use of offsets. Princeton’s current sustainability plan can be read at: http://www.princeton.edu/reports/sustainability2009/

District Energy System

District Heating
The district heating system distributes steam to over 0.9 million m\(^2\) (9.5 million ft\(^2\)) of building space representing a mix of uses including academic, research, administrative, residential, and athletic. Steam is produced using a gas turbine with a heat recovery steam generator (HRSG) and two auxiliary heat boilers. It leaves the plant at 1,380 kPag (200 psig) and is reduced with backpressure turbines, which generate electricity as they control the pressure, before reaching
customer buildings at 70 – 100 kPag (10 - 15 psig). In 2012, peak campus heat demand was 51 MW (175 MMBtu/hr) with an annual heating energy use of 160 GWh (545,000 MMBtu).

Steam is distributed through roughly 18 km (11 miles) of insulated steel pipes, and returned back to the plant through condensate piping with a condensate recovery between 70 and 90%.

**District Cooling**
The cooling plant uses a mix of electric centrifugal chillers with a total capacity of 37.5 MW (10,700 TR) and steam-driven centrifugal chillers with a total capacity of 36 MW (10,100 TR). Chiller production is coupled with a chilled water thermal energy storage (TES) system. The chilled water supply/return temperatures to the campus are 5.0/13.3°C (41/ 56°F), with higher supply temperatures when dehumidification is not required. In 2012, peak campus cooling demand was 50 MW (14,200 TR) with an annual cooling energy use of 116 GWh (33 million TR-hrs).

**Sustainable Energy Integration**

**CHP**
Princeton installed its CHP system in 1996 to support escalating electricity, heating and cooling needs on campus. The gas turbine is coupled with a duct burner and heat recovery steam generator (HRSG), and is capable of producing 15 MW of electricity and 53 MW (180 MMBtu/hr) of heat. CHP electricity output is about equal to the average campus demand. Peak campus electricity demand is 27 MW. To support peak steam load requirements and for reliability, there are also two auxiliary boilers with a combined capacity of 88 MW (300 MMBtu/hr).

The CHP system requires approximately 21% less fuel than typical onsite thermal generation and purchased electricity, reducing carbon dioxide emissions by an estimated 18,000 metric tons per year according to the United States Environmental Protection Agency (EPA).

**Biodiesel**
To further reduce greenhouse gas emissions, Princeton conducted tests in 2007 using soy-based biodiesel in its gas turbine and auxiliary boilers. The existing fuel permit had included only natural gas and ultra-low sulfur diesel oil (ULSD).

### Goals for biodiesel testing included:
- Demonstrate technical feasibility and obtain permit approval;
- Reduce on-campus emissions;
- Reduce cost of liquid fuel operation;
- Reduce campus total carbon footprint;
- Reduce use of foreign fuel;
- Potential to support local farmers and the domestic biodiesel market.

### Conclusions from the tests were:
- NOx emissions were similar to ULSD;
- CO emissions were notably better than ULSD (78% reduction);
- Engine exhaust temperatures exhibited less spread than ULSD;
- Less water required for NOx control.
Emission results were very good (see text box above). Fuel compatibility issues were minor and only a few minor upgrades, mostly related to materials, were required.

In 2008 Princeton received an operating permit revision to include biodiesel. The Princeton LM-1600 turbine was the first of its kind to be certified to operate on biodiesel fuel.

In 2009 a flue gas heat recovery system (FGHR) was installed to reduce fuel consumption by recovering heat from the exhaust stack. The system lowers the stack temperature from approximately 175°C (350°F) down to 82°C (180°F) and adds the recovered heat into the feed-water before the deaerator. It has been estimated that the FGHR reduces carbon emissions by 5,000 metric tons annually.

**Solar Photovoltaic System**
Princeton’s solar-collector field was installed in 2012 and includes 16,500 photovoltaic panels with a maximum output of 5 MW (direct current). Connected to the main campus’s power-distribution system, the field is anticipated to meet 5.5% of Princeton’s total annual electricity need and helps avoid production of 3,500 metric tons of carbon dioxide per year. Most of the solar power generation coincides with the highest daily utility rates.

**Chilled Water Thermal Energy Storage**
The TES system was installed in 2006 and has a capacity of 9,940 m3 (2.6 million gallons). It has a thermal storage capacity of 140 MWh (40,000 Ton-hours) with a peak discharge rate of 35 MW (10,000 TR). The storage tank is atmospheric and decoupled from the campus with heat exchangers. TES allows the campus to reduce cost and emissions and increase reliability and ease of operation:

- Costs are reduced by purchasing power at least cost.
- Energy use is reduced because chillers operate at the optimal design point and with lower nighttime wet-bulb temperatures. Lower temperature chilled water can be produced cost-effectively at night, enabling increased campus delta T and lower distribution pumping energy needs.
- Reliability and ease of operation are improved because production is decoupled from demand, chiller loading is consistent, daytime maintenance is easier, and peak demand is reduced.

**Ground source heat pump**
Princeton installed a 100-well ground source heat pump (GSHP) system in 2003 to serve 207 units at Lawrence Apartments. The University also conducted a GSHP study for the main campus to assess the potential to take advantage of this efficient technology. A lakeside residential complex and an arts and transit project that are both in construction include ground source heat pumps.
Key design interface challenges/solutions
In 2001, Princeton developed an economic dispatch model of the plant with an outside consultant. This system was designed to provide "expert guidance" for the plant operators. The system advises the operators based on 24 hour-ahead predictive modeling. The prices of imported electricity, natural gas, and diesel fuel are monitored in real time, as are the campus demands for electricity, steam, and chilled water. Operators make decisions on how much electricity to generate on campus and how much to import from the regional power grid based on that model.

The plant also has the ability to switch from natural gas to bio-diesel as price or supply dictates. (On extremely cold days when natural gas is in high demand, the gas provider can ask that the plant operators to switch to diesel operation. This allows Princeton to pay lower prices for natural gas.)

Electricity, imported or generated on campus, can be readily converted to chilled water and stored in the TES when it is cost effective to do so. Even on the coldest or hottest days there is a continuous need for both chilled water and steam on the campus.

The graph shows campus electricity purchase or generation for a typical summer day. During nighttime, when utility power prices are low, the University purchases electricity and CHP is run mainly for reliability. The increase in purchased power starting at 1 am and ending at 6 am indicates charging of the chilled water storage tank (to be utilized later in the day). At 7 am when the sun goes up the solar generation comes on. At 9 am when the price of utility power becomes more expensive, the University minimizes purchase of electricity and increases CHP output. The cycle repeats at 8 pm when the utility price again becomes low.
It is important to note that while some plant operations could be automated, the most important decisions are made by trained, licensed human operators. Those decisions are made based on the following criteria: safety, legal and regulatory constraints, reliability, environmental impact, and life cycle cost. The professional operators of the plant are absolutely essential to getting the greatest value from the facility. Safety, reliability, efficiency, and flexibility are the goals of the operation.

Through the use of CHP and TES, controlled with the predictive dispatch model, Princeton has been able to reduce peak purchased power from 27 MW to 2 MW.

*Thanks to Princeton University for photos, graphs and content contributions.*
9.13 Skagen District Heating System

Skagen, Denmark
Municipal utility provides heat and electricity utilizing waste fuel and renewable sources.

Sustainable Energy Technologies
Waste incineration, process waste heat, flue gas heat recovery, wind and thermal storage.

Organization and History
Skagen Varmevaerk was founded in 1963 and operates the district heating for the town of Skagen, the most northern town in Jutland.

District Heating System
The Skagen district heating system has a distribution network with more than 2,400 connected customers. Peak heat demand is approximately 30 MW (102 MMBtu/hr) with an average annual heat supply of 87 GWh (0.3 million MMBtu). The main plant also produces 24 – 30 GWh electricity annually.

The system has been designed for district supply and return temperatures of 100/40°C (212/104°F) with a minimum supply temperature in warm weather of 60°C (140°F). The space heating design temperatures for customers are 65/35°C (149/95°F).

The plant produces heat for the city and power to the grid, and consists of three CHP gas engines, four hot water natural gas boilers (prepared for the possible use of biodiesel), an electric hot water boiler and two hot water thermal storage systems. In addition to its own production, a municipal waste incineration plant and a nearby industry are also delivering heat to the district heating network.

Skagen Varmevaerk delivers heat according to the demand at the lowest possible cost. The required heat production, therefore, provides the framework within which electricity can be produced. The CHP engines are seldom run during nights and weekends when the electricity spot prices are low.

Sustainable Energy Integration
District heating production is derived from; natural gas CHP (37-43%), natural gas boilers (3-9%), waste incineration (35%) and industrial waste heat (19%). The two waste heat sources adequately fulfill the city’s minimum heat demand during the summer period.

Waste incineration
The waste incineration plant was connected to the district heating system in 1979 by the municipality of Skagen. This plant provides stable year-round heat production and runs as the base load plant for the system.
**Process waste heat**
Fiskernes Fiskeindustri is a privately owned industry that started to deliver process waste heat to the district heating system in 1982. Heat is delivered occasionally and based upon the industrial plant’s schedule and working hours.

**Thermal Storage**
There are two hot water thermal storage tanks installed with a total volume of about 10,000 m³ (2.6 million gallon), which corresponds to a capacity of 600 MWh (2,000 MMBtu) at a temperature difference of 52°C (94°F).

**Wind**
Provided that the electricity spot prices and the electrical network balances are favorable, 11 MW (37 MMBtu/hr) of excess electricity from wind energy production can be dumped into an electrical boiler and used as heat production for the DES. If there is no heat requirement, the thermal storage tank will be charged. Typically the spot price is low during nights and weekends, and the boiler can then be used for getting rid of excess electricity in the grid or to control the frequency of the grid.

**Flue gas heat recovery**
In 2012 three absorption heat pump machines were installed to recover heat from the flue gas stream generated by the natural gas driven CHP engines. Skagen Varmeværk already had economizers installed for this purpose. However, by installing the absorption machines the flue gas can now be cooled down even further to approximately 28°C (82°F), as compared to previously 60-65°C (140-150°F), before being discharged. Skagen Varmeværk expects to produce about 8-12,000 MWh (27–41,000 MMBtu) additional heat as a result of the additional heat recovery.

**Geoexchange**
Skagen Varmeværk has installed a ground source heat pump system which can provide heating and cooling to their office building.

**Key design interface challenges/solutions**
Besides selling electricity on the electricity spot market (Nord Pool Spot), Skagen Varmeværk participates in the market for regulating power (Regulating Power Market) and the market for frequency regulation (Primary Reserve Market). This requires a good knowledge of the plant’s capabilities, as well as good forecasting of market behavior. To handle these simultaneous production requirements effectively it is essential have very flexible operation, short start-up and shut-down capability, as well as operator alertness. The plant operates very much on the day-ahead estimates of the heat demand and electricity markets. The heat consumption can be flexibly managed through the thermal storage systems, and the CHP engines are continuously kept warm and prepared for an unlimited number of daily starts and stops.
Skagen Varmeværk has put flexible and adaptable operations at the heart of their business philosophy, and in 2010 actually managed to reduce the price of heating for its customers due to the additional revenue resulting from regulating power in the electricity market.

By law, energy companies in Denmark are obliged to achieve energy savings in enterprises and households by offering subsidies or consultancy. Currently (2013/2014), the energy savings obligation for energy companies is 2.6% of total energy consumption (75% increase compared to the 2010 level). Skagen Varmeværk uses a third party company, due to extensive administrative requirements, to buy and sell private homeowners energy savings (2,400 MWh annually).

*Thanks to Skagen Varmeværk for photos and content contributions.*
9.14 Southampton District Energy Scheme

Southampton, United Kingdom
Public-private partnership provides heating, cooling and electricity using geothermal and CHP.

Sustainable Energy Technologies
Deep geothermal and combined heat and power.

Organization and History
The Southampton District Energy Scheme was established in 1986 through a Joint Cooperation Agreement between Southampton City Council (SCC) and Utilicom (now Cofely District Energy Limited or CDE).

Following the dramatic rise in oil prices in the late 1970s, the Department of Energy established a research program looking into the potential for alternative energy sources in the UK, including geothermal heat from deep aquifers. Exploratory wells were drilled in various locations across the UK, including two in Southampton and one close to the City Centre. However, the capacity of the Southampton wells were deemed too small to develop a large-scale district heating scheme and the project was abandoned by the Department of Energy. The City Council refused to let the project fail and a new company was formed as a result of the Cooperation Agreement between CDE and SCC to develop the scheme.

The special purpose vehicle (SPV) company, established to deliver the scheme, Southampton Geothermal Heating Company (SGHC). The company is 100% owned by CDE but the partnership between the City Council and CDE has been critical to the scheme’s success. This partnership was renewed in 2005 for a further 25 years.

District Energy System
The district energy system is one of the larger commercially developed schemes in the UK. During a typical year, more than 40 GWh (135,000 MMBtu) of heat is delivered to 40 commercial and public sector customers and hundreds of domestic customers, 24 GWh
electricity is produced in the CHP plant and 7 GWh (2 million ton-hrs) of chilled water is delivered for air conditioning to hotels, retailers, civic buildings, TV studios and a leisure centre.

The geothermal well, currently undergoing a pump replacement, has a capacity of 2 MW (7 MMBtu/hr) and can provide up to 15% of the scheme's heat energy, while the CHP units with a combined capacity of 8 MW (27 MMBtu/hr) deliver approximately 70%. The remaining demand is supplied through conventional fossil fueled back-up/top-up boilers located in energy centers around the city. The district energy system has been designed to integrate the use of new emerging technologies and renewable energy sources such as biomass.

Hot water is distributed via 12 km (7.5 miles) of pre-insulated pipework within a 2 km (1.2 mile) radius of the main heating station. The scheme was developed on a low temperature, low pressure basis to reduce heat losses and maximize the life of the network. Supply temperature is varied seasonally between 70 - 82°C (160 - 180°F), with a return of 50°C (120°F). The system distribution pressure is approximately 5 barg (70 psig) and most customer buildings are directly connected (with no heat exchanger separating the district/primary system water from the building/secondary system water).

Both conventional chillers (using electricity from the CHP plant) and an absorption chiller (using surplus CHP heat), with a total capacity of 8 MW (2,270 TR), are used to produce chilled water for the district cooling system. An ice storage system is being considered to help meet the increasing peak load demands (the ice store would be frozen during the night and melted to provide cooling during the day).

There has been a $20 million investment to date in infrastructure, mostly financed by the Council's private partner but also with some EU and UK (HCA and EST) funding. Connections to individual developments are priced to provide consumers with a capital cost saving and customers can also expect 5 - 10% energy cost reductions against the conventional costs associated with heat and cooling energy.

**Sustainable Energy Integration**

**Geothermal**

A deep saline aquifer at a depth of 1,700 m (5,600 ft) and at a temperature of 76°C (170°F) rises naturally in the well to within 300 m (1,000 ft) of the surface. A maximum flow of 20 l/s (320 gpm) is then pumped to the heating station where its energy is transferred to the district heating system via titanium plate heat exchangers. The temperature of the well brine when reaching the heat exchangers is 74°C (165°F) and it is discharged to the sea at 28°C (82°F).

**Key design interface challenges/solutions**

**Technical**

The key challenge of this scheme was to work with each building developer/owner to design and operate their systems to provide the lowest possible return temperature, in order to maximize the use of the geothermal and CHP resources. SGHC endeavors to use direct connections into each building as much as possible. However, the standard approach of building services design in the UK, which results in poor return temperatures, has provided some challenges.
Business

Critical business success factors include:

- Strong and high level of political commitment.
- The creation of an interdepartmental working party, specially set up to implement and develop the scheme. This brought important experience and knowledge to the project and this approach also prevented potential delays that could have been caused by individual departments.
- A successful public-private partnership between the energy management company, with a track record of developing and running community heating schemes, and SCC, who actively encouraged new and existing buildings to connect to the scheme.
- The energy management company provided all the funding of the scheme (they own SGHC Ltd, the company set up to finance and run the scheme). SCC provided the land to build a heat station and the site of the geothermal well, in return for a long-term profit share.

From a commercial perspective it is important to engage the decision makers at an early stage in order to secure connections and to ensure there is a good understanding about the wide benefits that a connection can provide. In some cases senior Council officers wrote to the managing director informing them of the scheme and of the social, environmental and economic advantages that connecting to it can bring.

Hot and chilled water supply agreements with the consumers are typically for 20 years. These agreements are essential to obtain the long-term financing needed for developing the network and integrating sustainable energy plant into the scheme. This also benefits the customers in the form of highly competitive tariffs for heating and cooling, linked transparently to published indices over the life of the supply agreements to guarantee continuing cost savings.

Thanks to CDE for photos and content contributions.
9.15 Stanford University Chiller Heat Recovery

Stanford, California, USA
University converts from Co-generation to Re-generation utilizing heat recovery chillers and thermal energy storage.

Sustainable Energy Technologies
Heat recovery chillers, thermal energy storage and geoexchange.

Organization and History
Along with strong new building energy efficiency standards to reduce the impacts of growth and conservation measures to reduce energy use in existing facilities, an innovative energy supply is the third key strategy of Stanford’s Energy and Climate Plan for the period 2010 – 2050.

The campus has used natural gas fired CHP to provide its energy since the late 1980’s. However, new information about the impact of fossil fuel use on climate change and changes in energy costs led the university to implement heat recovery chillers in its pursuit of an efficient and sustainable energy supply.

District Heating and Cooling System
Today Stanford University is served by third party owned and operated natural gas fired combined heat and power (CHP) plant. Heat is produced in the CHP and transported via a steam district heating system to buildings for space heating and domestic hot water use. In the cooling process unwanted heat is collected from buildings and transported by a chilled water district cooling system to evaporative cooling towers where it is discarded to the atmosphere.

Implementation of the Energy and Climate Plan includes following changes:

- Achievement of new building energy efficiency standards of 30% below code.
- Continuance and expansion of energy conservation in existing buildings.
- Moving to University owned and operated hot water boilers, chillers, and heat recovery plant with imported off-site grid electricity.
Major changes to campus infrastructure, most notably conversion of the campus steam distribution system to hot water (30,000 trench meters or 100,000 trench feet) and building conversions (155 buildings).

The new hot water system together with connected buildings will be designed for a supply/return temperature of 77/55°C (170/130°F) with a reset schedule down to a minimum supply temperature of 65°C (150°F). The low temperature program ensures high seasonal heat recovery efficiency and provides flexibility for adoption of new energy supply technologies and innovations that may develop in the future.

Additional benefits when converting the campus steam distribution system to hot water, beyond facilitating the deployment of heat recovery, include the following:

- Heating system distribution losses will be reduced from about 12% to 4%.
- Operation and maintenance cost will be much lower with the hot water system.
- Substantial capital costs for replacement of aging portions of the steam system will be avoided through the conversion.
- Capital costs for future system expansion and interconnection to new buildings will be much cheaper.

Sustainable Energy Integration

Stanford University has employed energy metering at all its facilities for over ten years to better understand how and where energy is being used. Analysis of hourly heat and chilled water production data revealed that heat recovery chillers can be used to capture 70% of the unwanted waste heat from the chilled water system for re-use in the hot water system to meet 80% of campus heating needs. It is important to note that this level of simultaneous or near-simultaneous heating and cooling that exists at Stanford represents a relatively unique climate situation.
Furthermore, because evaporative cooling towers are currently used for discharging heat from the cooling process to the atmosphere, a significant amount of campus overall water usage can be saved through heat recovery (18-25%).

Implementation of the Energy and Climate Plan will reduce greenhouse gas emissions by 75 - 80% of the 2000 baseline by 2020 and provide opportunities for even higher reductions by 2050 should regulatory and economic conditions allow.

**Heat Recovery Chillers (HRC) and Thermal Energy Storage (TES)**  
The new Central Energy Plant will include three heat recovery chillers, four conventional chillers, three natural gas fired hot water boilers, two cold water thermal storage tanks and one hot water thermal energy storage tank. Thermal energy storage is not only more economical in up-front capital cost than adding more hot water and cold water production capacity but it also allows: 1) the capture and reuse of more waste heat than would otherwise be possible with a “real-time-only” heat recovery process; and 2) ishifting of equipment production work to night and weekend periods of lower cost electricity.

HRC will run all year round but with a heat rejection temperature that varies with the district heating supply temperature requirement from 65-77°C (150-170°F). Low temperature difference between heat source (DC) and heat sink (DH) is essential since HRC efficiency deteriorates with high temperature difference.

**Ground Source Heat Exchange**  
Ground source heat exchange to meet the remaining 30% of thermal needs is an enhancement currently under study.
Unlike closed loop ground source heat exchange in static ground conditions where seasonal heat exchanges must be balanced to avoid over-heating or over-cooling the ground, the plan at Stanford is to use an open loop system with the ground water used as a continuously replenishing heat source or sink as needed. This will allow Stanford to take or deposit low grade heat energy to the groundwater as needed.

While the bulk of heat extraction will occur in wintertime and the bulk of heat rejection in summertime, plant operational models show that both will occur on a daily basis throughout the year. Although described as an “open loop” process the ground water never comes into direct contact with the district heating water but will be separated using a heat exchanger. Typical ground source injection and extraction temperatures currently under evaluation are 9/17°C (48/62°F).

**Key design interface challenges/solutions**

**Technical**

Lessons learned include:

- A predictive thermal energy plant equipment dispatch model that could look at least 168 hours in advance (one week to always capture lower cost weekend electricity) and optimize plant operations did not exist and had to be created. This model was not only critical in proving the heat recovery concept savings and sizing of equipment but will also be used when operating the plant to assure it achieves maximum efficiency, sustainability and economic goals.
- Integration of the dispatch model software with “conventional” plant controls was necessary and required selection of a plant controls provider with a capability and willingness to perform this advanced integration.
- Only one manufacturer was found in the USA that currently provided high capacity and high efficiency HRC, so other manufacturers had to be approached to develop other competitive options.

Lessons learned relative to the underground hot water distribution network installation:

- Quality surveying is essential to avoid existing utilities and limit field changes.
- Procurement of European manufactured HW piping system material adds minor procurement time to the project but saves far greater time and cost in installation than conventional North American methods.
- Welding and joint kits are key factors to production rates.
- Alarm wire connections are sensitive and can cause delays.

Lessons learned relative to the building conversion:

- Hot water supply and return temperatures--
  - Testing at low supply temperature is critical to understand building conversion needs.
  - It is useful to target the buildings that are easiest to convert and/or are important for the total system return temperature.
Buildings with constant speed pumps and 3-way valve control require much work.

- Skid mounted Energy Transfer Station (ETS) equipment was very helpful by moving labor off-site.
- Greatest risk of cost overruns results from--
  - Unidentified heating devices.
  - Phasing and outages.
  - Time and effort for survey and documentation.

**Business**

By significantly decoupling the campus energy supply from fossil fuel, greater operating budget stability is provided and economic, regulatory and public relations risks are reduced.

Implementation of the Energy and Climate Plan covers the period 2010 - 2050 and involves:

- Total capital investment of $438 million ($69 million or 13% more than the business-as-usual case).
- Cost savings of $639 million over the business-as-usual case (third party cogeneration).
- Total campus water savings of 18-25% over current projections.

The major capital cost of the project (49%) relates to the conversion of the steam distribution and condensate return pipelines to hot water, whereas the new central plant facility is 39% and new substations 12% of capital costs.

*Thanks to Stanford University for photos, graphs and content contributions.*
9.16 Turku Energy District System

Turku, Finland
City provides heating, cooling and electricity using renewable sources such as biomass and wastewater heat pump.

Sustainable Energy Technologies
Waste heat from wastewater treatment plant, biomass plant, and thermal energy storage.

Organization and History
Turku Energy is a joint-stock Power Company owned to 100% by the City of Turku, located in southwest Finland. The company was founded in 1994 and serves private consumers, companies, and communities.

District Energy System
The Turku Energy district system is a municipal scheme with more than 12,000 users. The district heating network now covers about 90% of the residents.

Sustainable Energy Integration
In 2009, 30% of the energy used for district heating was from renewable fuels such as wood-based fuels, heat pumps, and biogas. By 2020 the goal of Turku Energy is to increase the amount of renewable energy sources in district heating to 50%.

Oriketo Biomass Plant
The Oriketo biomass fired district heating plant, with 40 MW (137 MMBtu/hr), and condensing units with 12 MW (41 MMBtu/hr), is located in the industrial area of Turku and was commissioned in 2001. The main fuel is logging residue delivered from final felling of spruce-dominant forests in the surroundings. Heat generated by the station replaces fossil fuel needs and the annual heat production is about 300 GWh/year (1,000,000 MMBtu), which corresponds to about 20% of the district heating for the Turku region.
As a result of the biomass plant, annual CO2 emissions have been reduced by about 90,000 tonnes, SO2 emissions by about 300 tonnes and NOx emissions by about 70 tonnes.

**Thermal storage**
In 2002 an old gas storage was converted into a modern district heating thermal storage. As a result, it was possible to save and renovate a historically valuable building and 20 GWh (68,000 MMBtu) of annual oil use for energy production, resulting in a saving of approximately 2,000 tons of oil.

The thermal storage is used to store hot water for the district heating system during low consumption periods which can later be used during consumption peaks. As a result, this initiative allows production units to work in a more efficient way.

**Wastewater utilization in Kakola heat pump plant**
The Kakola wastewater heat pump plant was commissioned in 2009. The wastewater treatment plant treats over 100,000 m3 (26 million gal.) per day and uses the waste heat via a heat pump to produce both heating and cooling for public buildings and homes in the city of Turku.
The heat pump plant’s heat output is 19.5 MW (67 MMBtu/hr) and its 2010 yearly production output was 170 GWh (580,000 MMBtu). The heat pump is able to cover 10% of the district heating demand. The heat pump can produce district heating water at almost 90°C (195°F).

The heat pump plant’s cooling output is 13 MW (3,700 TR) and its 2010 yearly production output was 70 GWh (20 MMTR-hr). The plant is able to cover 80% of the district cooling demand.

Installation of the heat pump plant reduced the amount of coal burned by 21,000 tonnes per year, resulting in a reduction of CO2 emissions by about 50,000 tonnes, SO2 emissions by about 110 tonnes and NOx emissions by about 110 tonnes.

The silt which arises in the wastewater cleaning process is used to produce methane gas in a biogas plant. Biogas is an environmentally friendly, domestic and renewable source and used to produce district heat and electricity. Treated silt is used as soil improvement material and therefore substitutes for artificial fertilizers and facilitates soil microbial action.

**Cooling Thermal Storage**
To balance the daily fluctuations and provide momentary increases in cooling load to the district cooling network, a 15,000 m3 (4,000,000 gal.) chilled wastewater accumulator is installed near the heat pump.

**Key design interface challenges/solutions**

**Technical**
The most difficult challenge with the Kakola heat pump plant was the fast timetable with lot of different operators. The project was realized with tight cooperation with Turku region’s municipality, the plant’s neighbors and many different local authorities.

**Business**
Construction costs for Oriketo biomass fired district heating plant were 14 million Euros and another 3 million Euros for installation of the hot water thermal storage tank. All investments were made by Turku Energy; there were no other partners involved.

The Kakola heat pump plant project was financed by Turku Energy together with water treatment and biogas parties and some funding from the Ministry of Trade and Industry. Turku Energy’s investment was 12.5 million Euros.

*Thanks to Turku Energy for photos, graphs and content contributions.*
9.17  Vancouver Sewer Heat Recovery

Vancouver, British Columbia, Canada
Municipal thermal utility provides heating using waste heat from sewer and solar collectors.

Sustainable Energy Technologies
Sewer waste heat, solar thermal.

Organization and History
With a keen interest in building a highly sustainable community for the 2010 winter Olympics, the City of Vancouver evaluated various alternatives and eventually chose the district energy concept. Construction began in 2007 to serve the Athlete’s Village. The Southeast False Creek community is built on an 80 acre brownfield site that had seen 120 years of industrial use. By 2018 the district energy system is expected to expand to serve 560,000 m² (6 million ft²) of development with 16,000 new residents.

District Energy System

*District Heating*
There are presently 18 buildings connected to the hot water district energy network, and current expansion will add 7 more over the next 2 years. The total connected building space is about 250,000 m² (2.7 million ft²), which will have a diversified load of approximately 14 MWt (48 MMBtu/hr) at full occupancy. All buildings are designed to return low temperature water, which accommodates different sources of waste heat energy.

About 70% of the annual heating energy consumption is supplied by heat pumps that draw energy from the community’s sewer, and the remaining demand is provided by high efficiency natural gas boilers and solar thermal modules.

Excess solar heat is recovered from roof-mounted solar thermal arrays located on three buildings and the building owners receive credits for the energy they put into the community system.
The capital cost as of 2011 was C$33.8 million (the cumulative cost grows each year as the connected floor area grows and additional production, distribution piping, energy transfer stations are added). This figure does not include an additional C$8.5 million for the pump station upgrade that fell under the maintenance budget. The construction financing was provided by a combination of a provincial grant (a transfer from a federal source), a low interest federal loan, and capital from the city’s capital financing fund.

**Sustainable Energy Integration**

**Heat Pumps**

The key to providing environmentally responsible, low carbon renewable energy is the waste heat recovery from the community’s sewer at a temperature of 20±2°C (68±3.6°F). In the first stage the heat recovery consists of two heat pumps with 3.0 MWt (10 MMBtu/hr) of capacity operating in series/parallel configuration with output temperature ranging from 65-80°C (149-176°F). The design allows for a total of four heat pumps to be installed as the system grows. The weighted average heating COP for the system has been 3.3.

**Solar Thermal**

During peak sunlight periods, the roof-mounted solar systems can generate a surplus of heat in excess of the building’s demand. This excess heat is sold back to the thermal utility (50% of the sell rate) through each building’s ETS and is shared through the main piping system for use in other buildings that are net energy users - effectively reducing the electrical energy consumption of the heat pumps. Solar thermal collectors provide the majority of energy in the summer months at a time when the efficiency of the heat pump system is significantly reduced.

**Key design interface challenges/solutions**

Key development strategies that contributed to the project’s success are summarized below.

**Technical**

- Experienced consultants -- Engineering consultants who are experienced with district energy design helped minimize the cost associated with the technical and performance risks associated with the incorporation of renewable generation.
• Previously tested and flexible systems - The use of well-established European Standard district energy distribution systems design standards (e.g. pre-insulated piping with leak-detection and energy transfer stations).
• Staged approach to installing energy generation equipment – matching energy supply with energy demand by spreading out the deployment of capital and reducing the debt interest burden.

**Business**
• Public consultation – Engaging stakeholders in the project’s development to ensure buy-in.
• Public funding - Assistance of a federal grant for a portion of the phase 1 cost and the access to low interest debt financing.
• Capital cost recovery structure – Using a levelized rate-setting approach with access to a revolving line of credit to offset capital cost under-recovery in the early years of operation due to a low number of ratepayers during that period.
• Granting of ‘General Supervision’ status by the Safety Authority - This reduced the utility’s operating costs by eliminating the requirement for 24/7 supervision by a licensed power engineer.

*Thanks to City of Vancouver for pictures and content contributions.*
9.18 District Energy St. Paul (Overview)

St. Paul, Minnesota, USA

Private non-profit thermal utility provides heating, cooling and electricity using local waste wood

Sustainable Energy Technologies
Biomass, Combined Heat and Power, solar thermal, chilled water thermal energy storage.

Organization and History
District Energy St. Paul is a private, non-profit thermal utility established through a public-private partnership with the City of Saint Paul, State of Minnesota, U.S. Department of Energy and the downtown business community. The initial hot water district heating system began operating in 1983, and in 1993 a district chilled water system was developed to help customers respond to once-through cooling restrictions (use of groundwater for air conditioning and subsequent dumping of the water) and the phase-out of CFC refrigerants.

District Energy System

District Heating
District Energy St. Paul is the largest hot water district heating system in North America and is recognized throughout North America as a community model and a leader in renewable energy. It currently provides heating service to 195 buildings and 300 single-family homes, representing over 3 million m$^2$ (32 million ft$^2$) of building space, or 80% of St. Paul’s central business district and adjacent areas.

The hot water supply temperature varies from 120°C (250°F) under winter peak conditions to 82°C (180°F) during summer. Peak load requirement is 289 MW (987 MMBtu/hr) with an annual sale of 340 GWh (1,200,000 MMBtu). Hot water is distributed through insulated steel pipes, with 32,000 trench m (105,000 ft) of supply and return piping.

The heating system has the flexibility to use a variety of fuels. Initially coal was the primary fuel, with some natural gas and oil consumption. Now biomass is the primary fuel and is used for combined heat and power as discussed below. Solar thermal capacity was installed in 2011 and is briefly described in this case study, with the next case study providing detailed data on the solar installation. The shift from fossil fuels resulted in a reduction of sulfur dioxide emissions by roughly 600 metric tons and carbon dioxide emissions by 280,000 metric tons annually.

District Cooling
The cooling system now serves over 1.85 million m$^2$ (20 million ft$^2$) of building space. The chilled water supply temperature is generally 5.5°C (42°F), with warmer temperatures during the cooler months. Peak load requirement is 123 MW (35,000 TR) with an annual sale of about 130 GWh (38 million TR-hrs).
Chilled water is distributed through steel pipes wrapped in protective coating, with about 11,000 trench m (36,000 ft) of supply and return piping. The cooling plant uses primarily electric chillers, with steam absorption chillers driven by low-pressure steam from CHP.

**Sustainable Energy Integration**

**Biomass Combined Heat and Power**

In 2003, District Energy developed a biomass CHP facility capable of producing 33 MW of electricity and 65 MW (220 MMBtu/hr) of heat. 25 MW of power is sold to the local electricity utility under a 20 year agreement. The CHP facility provides 70% of the annual energy heat production and consumes waste wood from downed trees, trimmings and branches (300,000 ton/year). This is roughly half of the wood waste generated annually in the metropolitan area.

By turning regional wood waste into a useful product, the system keeps about $12 million of the community’s annual energy dollars in the local economy. Making use of this wood waste also helps solve an ongoing environmental challenge, since much of it had gone to landfills or was burned in open fires.

**Solar Thermal**

The Saint Paul RiverCentre solar installation in downtown Saint Paul was the first solar thermal facility in the USA to be integrated with a district energy system. It consists of 144 Arcon solar thermal collectors (1,948 m² or 21,000 ft² collector area) located on the convention center’s North and South penthouse roofs. The system, installed in 2011, generates a nominal output maximum of 1.2 MW (4.1 MMBtu/hour) and provides about 1 GWh (3,500 MMBtu) of heat annually.
The piping configuration uses the supply line to export heat to the district energy system, allowing the adaptation of solar thermal to the district energy heating loop without additional piping. An earlier option considered heating the return water and exporting it back to the district energy return line. This would require significant additional piping run through the existing building, necessitating significant demolition and subsequent patching. The selected means of return to supply is the best design compromise, in that it starts with the lower temperature return water and avoids the construction cost of adding a third line to tie to the heating loop.

The project has lowered the carbon footprint for the system and further diversifies fuel flexibility. It was funded with federal assistance and total investment was 1.7 million Euros ($2.25 million).

**Thermal Storage**
Two water storage tanks -- 9,500 and 15,000 m³ (2.5 and 4.3 million gal.) -- enable the company to generate chilled water using low-cost nighttime power. Storage provides lower cost peak cooling capacity and additional operational flexibility, and reduces peak electricity demand by approximately 9 MW.

In 2013, one of the tanks was converted to allow transition seasonally from chilled water to hot water storage. This conversion will delay start of fossil fueled peak boilers, which allows use of more biomass as well as integration of a flue gas heat recovery system.

**Key design interface challenges/solutions**
Key challenges for turning regional waste wood into a useful product included:

- Availability/location/sustainability;
- Quality;
- Variability/seasonality of supply;
- Competition;
- Logistics – transportation and storage; and
- Fuel handling system design.

Key challenges for integrating solar heat into the district energy system are discussed below.

**Design aspects**
Collector performance (and related energy production) turned out to be a crucial aspect of the project feasibility. It was found that collector net efficiency varies heavily between suppliers in the market and the difference in produced energy per year could be as high as 0.6 to 1.

When installed together with a host building, thermal load and temperature characteristics of the targeted building should be carefully studied before implementation. There will be periods when the solar thermal load capacity is only enough for the host building. If this can be run with low temperatures, a higher collector panel net efficiency can be obtained since collector performance deteriorates with higher temperatures.

**Construction aspects**
Structural vulnerabilities may contribute significant additional costs, and solar collectors construction load could be substantial (collectors, piping, snow, ice and wind load). Structural implications of solar projects should be identified prior to construction for optimal savings.
Projects should be selected based on structural integrity and lowest reinforcement costs. Ideally, ground standing projects will save the most on capital and engineering if soil conditions and southern exposure are ideal.

Although there are many high-performing international manufacturers, shipping and unloading large collectors can be a challenge. Project developers should identify local offsite delivery points for local pickup and delivery responsibility by the contractor. This can avoid unnecessary delays, and hidden costs associated with import, ocean transport, rail and unplanned storage.

**Control aspects**
Control installations should maximize integration between existing building controls and additional solar controls. If the systems are well-integrated the conventional system could be programmed to anticipate and to a greater extent accommodate solar energy and thus maximize available energy. A pyranometer (solar irradiance reading) can be used to guide operational modes such as startup, export mode, etc.

Preferably the control system should also be programmed to take advantage of low grade heat prior to reaching elevated temperatures. For example, cold DHW can be preheated before contributing to space heating.

Instrumentation redundancy and data collection is ideally planned at the onset of a project. A set of commonly needed data points should be determined by all parties involved.

Metering and controls can be a costly portion of the system, but controls investments can help optimize the long-term performance of the system and the resulting economic benefits.

*See the next case study (St. Paul Solar Thermal Project) for detailed information about the solar installation.*

*Thanks to Ever-Green Energy for photos and content contributions.*
9.19 St. Paul Solar Thermal Project (Detailed Case Study)

Introduction

Solar energy is shifting from a novel idea to a growing energy option for utilities, businesses and residents. In 2010, District Energy St. Paul launched the largest solar project in the Midwest on the roof of the local convention center, the Saint Paul RiverCentre. The 144 collector system became operational in March 2011, and produces 1.2 MW (4.1 MMBtu/hr) peak thermal energy. This large-scale, high-performance showcase system reduces the carbon footprint of the system and further diversifies fuel flexibility. This installation is the first solar district energy system in the United States. Key data are summarized below.

<table>
<thead>
<tr>
<th>Location</th>
<th>Saint Paul, Minnesota</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>44.95°N</td>
</tr>
<tr>
<td>Longitude</td>
<td>93.1°W</td>
</tr>
<tr>
<td>Total Collector Area</td>
<td>1,948 m² (20,968 ft²)</td>
</tr>
<tr>
<td>Solar Irradiation (annual)</td>
<td>1680 kWh/m² (532 MBtu/ft²)</td>
</tr>
<tr>
<td>Application</td>
<td>Solar hot water serves the host building first, including domestic hot water and space heating. Excess heat produced is exported into the district hot water heating system.</td>
</tr>
<tr>
<td>Year of operation start</td>
<td>2011</td>
</tr>
</tbody>
</table>

Table 6. St. Paul Solar Installation General Information

District Energy St. Paul currently provides heating service to 195 buildings and 300 single-family homes, representing over 3 million m² (31.7 million ft²) of building space, or 80% of Saint Paul’s central business district and adjacent areas.

Project Objectives

This project was intended to demonstrate the value of using large-scale solar thermal integrated into a district heating system, and was designed to address these barriers:

- Low effective market penetration of solar thermal systems. This project serves as a visible reminder of the potential for solar thermal. Although there have been local programs to encourage solar thermal in small, independent residential applications, this region has not been exposed to a large-scale practical application or the potential to connect and/or store the thermal energy created.
• **Lack of viable and tested business models for using solar thermal to connect energy needs in multiple buildings.** Both district energy and solar thermal are widely integrated in Europe because of their high efficiency and economic benefits. Despite the proven technical feasibility, there were no current examples of a USA solar thermal installation being used to service multiple buildings. This project provided exposure to planners, developers, and energy consultants to the viability of these types of installations.

• **Lack of funding for implementing large scale solar projects.** Given the financial constraints for today’s city managers and planners, it is important to work with private parties to identify ways to continue to expand the solar market. Utilities play an important role in energy planning and delivery and are ideal partners, particularly when there is a financial commitment to expand solar within their resource portfolios.

**Key Project Characteristics**

Preliminary engineering indicated potential for multiple customer buildings on the District Energy St. Paul system and sufficient energy output to justify the capital investments, with the support of the Solar America Cities grant funds. System design was initiated in January 2010, focusing on three primary areas: 1) collector technology 2) site-specific considerations; and 3) district heating integration.

As part of the preliminary engineering completed in 2009, District Energy performed a market assessment of commercially available thermal and thermal/PV collectors. Due to project and licensing requirements, an emphasis was placed on products certified through Solar Rating & Certification Corporation (SRCC). Verifying these findings was important to the design process, so an additional Request for Qualifications (RFQ) was completed in March 2010. Eight companies submitted products for consideration, two of which manufactured in the United States. The RFQ information was then used to complete preliminary system design, which was necessary to formally bid the collectors.

The formal bidding process began in May 2010. Collector performance (and related energy production) is the most crucial aspect of project feasibility, although the collectors only account for 16% of the project budget. Other very important aspects for project feasibility include characteristics of the building targeted for installation. Since construction was relatively recently completed on this solar thermal district energy system, the opportunities to learn from the project are still being defined.

**Project Site**

The District Energy St. Paul service area is illustrated in Figure 45, noting the location of the main plant and the site of the solar installation. The St. Paul RiverCentre solar installation consists of 144 Arcon 13.5 m² solar thermal collectors (1,948 m² or 21,000 ft² collector area) on the convention center’s North and South penthouse roofs (2,880 m² or 31,000 ft² roof area).
Site characteristics will always play a major role in system design. At the selected site, building roof material was approaching the end of its useful life, making it necessary to be replaced before starting construction of the solar project. The structural engineering review of the building determined that additional structural supports were necessary before the collectors could be installed on the roof. See Figure 46.

The site was selected for its location within the bounds of the District Energy heating loop, its lack of shading or adjacent obstructions and its compatibility with district energy and subsequent ease of adaptation for solar thermal.
The solar collectors are mounted to a galvanized heavy (up to W16 x 26) structural steel structure laid out on a 9.1 x 9.8 m (30’ x 32’) grid. The grid points are mounted to extensions on the building’s existing columns, which carry the entire load, leaving the exiting roof structure’s loading unchanged. Each collector consists of five sheets of glass assembled with an aluminum frame making one 260 kg (570 lb.) unit, approximately 2.5 x 6 m (8’ x 20’). The reason for such a heavy structure is that the steel must carry the weight of the collectors, the piping, and their snow, ice and wind load plus the structure’s own weight. See the following two Figures.
Collector Technology

The bid specification was developed as follows. The performance requirements were based on energy production at a given ambient outdoor temperature. The collectors must produce high output temperatures and withstand high system pressures and flow rates. Collector design was rated for a maximum operating temperature of 121°C (250°F) and 1034 kPag (150 psig) maximum operating pressure at this temperature. Key collector design criteria included:

- Collectors are designed to withstand stagnation temperature conditions associated with an extreme ambient temperature of 40°C (104°F) on a clear day. Collectors were designed to withstand 1034 kPag (150 psig) internal pressure at this condition.
- Collectors weighing app. 25 kg/m² (5 lbs/ft²) of gross collector area (full) or less are preferred.
- Insulating materials will not out-gas or break down at, or under, stagnation temperature.
- Collector heat loss will be less than 4.0 W/(m² K) or 0.70 Btu/(hr-ft²·°F).
- Collector starting efficiency shall be a minimum of 0.70 for flat type collector.

After completing the collector solicitation and review, no responding USA manufacturer could meet the technical requirements or production deadlines of the project. (As of June, 2012, two U.S. manufacturers were preparing high-performance industrial solar thermal collectors for market.)
Eight (8) bids were received including six (6) manufacturers located outside the USA. One US manufacturer failed to meet the technical requirements, certification, and quantity requested.

The other US manufacturer would produce 41% less energy per year than the Arcon HT-SA 28/10 collector and it appears they could not supply adequate quantities. A full installation comprised of these collectors would result in a 0.6 MW (2 MMBtu/hr) peak system versus the 1 MW (3.4 MMBtu/hr) expected from the project as implemented.

Efficiency performance data for the different collectors is shown in Figure 49, with the x axis being the temperature difference between the collector output and the ambient temperature.

![Gross Area Performance Data](image)

**Figure 49. Collector Efficiency Data for Competitive Bidders (at varying degrees C difference between collector temperature and ambient)**

The collectors used in this system, Arcon HT-SA 28/10, could meet the peak and expected annual output using the available roof space, and are very efficient even at low ambient and high operating temperatures. The collectors were chosen based on their potential to collect the most energy per area roof space required, while maintaining required operating temperatures.

Solar collectors have a net efficiency which is a factor of how much of the available solar energy they collect. This factor is made up of two parts, starting efficiency and thermal losses. The starting efficiency is a measure of the solar energy available they are capable of collecting. The thermal losses is a measure of the available solar energy lost to the ambient surroundings at a given operating temperature and ambient air temperature.
Arcon’s collector has a performance advantage due to the development of collector components for maximum efficiency. These subtle, notable characteristics allow them to have the highest net efficiency of any collectors submitted in the project’s public Request for Information. The selected collectors have a gross collector area starting efficiency of 0.754 and gross area thermal losses of approximately 2.2 W/(m² K) or 0.39 Btu/(hr-ft²-°F).

The glass used has low iron content for improved clarity to allow maximum irradiance and it uses an anti-reflex coating to minimize what is reflected off its surface. Irradiance refers to the amount of solar energy that arrives at a specific area at a specific time and is measured in W/m². The collector uses an Ethylene Tetra Flouro Ethylene (ETFE) clear film behind the glass that lets light through but limits heat from escaping from the collector’s face. See Figure 50.

There is a very efficient internal collector surface to absorb the sun’s energy. The manufacturing technique joining the collector surface to the fluid tubes maximizes heat transfer between the two. For conventional insulation there is 30 mm (1 ¼”) mineral wool on the sides and 75 mm (3”) on the back. The Arcon collectors have a gross area instantaneous net efficiency range of 0.754 to around 0.55 in their operating range. This compares to a range of under 0.70 to less than 0.40 in the same operating range with otherwise comparable collectors. This advantage is in effect at nearly all irradiance levels and operating temperatures.

The system uses a 50/50 mix of propylene glycol and demineralized water. It is a very high quality heat transfer fluid with a slushing temperature of -40°C (-40°F) and a boiling temperature of 232°C (450°F). Each collector contains just under 10 liters (2.5 gallons) of the fluid often referred to simply as glycol.
The collectors were mounted at a 45° angle to maximize energy collected in the spring and the fall when there is both significant heating load in the building and relatively high solar irradiance (see Figure 52). This is the best compromise of when the maximum amount of solar energy is available in the summer (which would require a flatter angle) and when the maximum load occurs in the winter (which would require a steeper angle). The collectors are aligned with the building in three rows (see Figure 53) on each roof running the entire length facing south.
Components of the installation are illustrated on the following 2 pages, and detailed data are provided in Table 7.
Panels

- 8’ x 20’ Panels
- 5 Sheets of glass = 1 panel
- 144 Panels
- 3 Rows
- Series of 7 per bank
- Flexible hoses connect panels

Pyranometer

Flexible Hoses
Figure 54. Components of Installation
<table>
<thead>
<tr>
<th><strong>Brand of Collector</strong></th>
<th>Arcon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collector Specification</strong></td>
<td>Standard flat plate collector</td>
</tr>
<tr>
<td><strong>Angle</strong></td>
<td>45°</td>
</tr>
<tr>
<td><strong>Orientation</strong></td>
<td>186° South</td>
</tr>
<tr>
<td><strong>Start Efficiency ($\eta_0$)</strong></td>
<td>0.754 Gross Area 0.817 Net Aperture area</td>
</tr>
<tr>
<td><strong>Loss Coefficient ($a_1$)</strong></td>
<td>2.2035 W/(m²K) Gross Area 2.205 W/(m²K) Aperture area</td>
</tr>
<tr>
<td><strong>Loss Coefficient ($a_2$)</strong></td>
<td>0.0135 W/(m²K²)</td>
</tr>
<tr>
<td><strong>Total Collector Area</strong></td>
<td>1,948 m² (20,968 ft²)</td>
</tr>
<tr>
<td><strong>Total Roof Area</strong></td>
<td>2,854 m² (30,720 ft²)</td>
</tr>
<tr>
<td><strong>North Roof Length</strong></td>
<td>128 m (420 ft)</td>
</tr>
<tr>
<td><strong>South Roof Length</strong></td>
<td>165 m (540 ft)</td>
</tr>
<tr>
<td><strong>Collector weight dry</strong></td>
<td>250 kg (550 lb.)</td>
</tr>
<tr>
<td><strong>Collector weight wet</strong></td>
<td>260 kg (571 lb.)</td>
</tr>
<tr>
<td><strong>Propylene Glycol capacity</strong></td>
<td>4.5 m³ (1,200 gallons)</td>
</tr>
<tr>
<td><strong>Design Annual Energy</strong></td>
<td>1,261 MWh (4,303 MMBtu)</td>
</tr>
<tr>
<td><strong>Measured Annual Energy - Total</strong> (most recent 12 months)</td>
<td>1,006 MWh (3,433 MMBtu)</td>
</tr>
<tr>
<td><strong>Measured Annual Energy – Export</strong> (most recent 12 months)</td>
<td>688 MWh (2,347 MMBtu)</td>
</tr>
<tr>
<td><strong>Design Peak Capacity</strong></td>
<td>1.1 MW (3.8 MMBtu/hr)</td>
</tr>
<tr>
<td><strong>Measured Peak Capacity</strong></td>
<td>1.2 MW (4.1 MMBtu/hr)</td>
</tr>
<tr>
<td><strong>Design solar fraction of peak load requirement (per host building)</strong></td>
<td>42.7%</td>
</tr>
<tr>
<td><strong>Design solar fraction of peak load requirement (per district energy system)</strong></td>
<td>0.351%</td>
</tr>
<tr>
<td><strong>Measured solar fraction (per building)</strong></td>
<td>29.43% on premises</td>
</tr>
<tr>
<td><strong>Measured solar fraction (per system)</strong></td>
<td>0.10%</td>
</tr>
</tbody>
</table>

*Table 7. Solar System Specifications*
Manifold

Collectors are connected to a manifold header running below the front of the collectors (see Figure 55 for a close-up view and Figure 56 for a view of the entire manifold system). Seven collectors are banked in series between connections. Each collector has one inlet and one outlet on the top of each end, and flexible hoses are used between collectors and at the end of each bank. There is a common header between the north and south roofs. A drop from this header leads to a previously existing mechanical area on the floor below the roof. A steel/polyurethane/polyethylene pre-insulated system is used for all of the exterior piping. Mounted to the vertical drop is the solar irradiance meter, or pyranometer. The pyranometer has the same orientation to the sun as the collectors and continuously measures the instantaneous unit energy of the sun imparted on the surface.

Figure 55. Manifold Pipe
Mechanical Area

The mechanical area (Figure 57) consists of plate and frame heat exchangers and pumps that transfer the energy in the solar glycol system to the multiple heat applications, including the host building’s on-site systems and the District Energy St. Paul heating loop serving the downtown area. Prior to the solar installation, the mechanical area utilized some pumps, a heat exchanger, expansion tanks and a domestic hot water storage tank. The area is located conveniently below the roof housing the collectors. Adjacent to it is an electrical room that now contains VFDs for the pumps.

An overview schematic is provided in Figure 58.
Heat Exchangers

PHX – Primary
AHX – Air Handling
DHX – Domestic Hot Water
WWH1 – Non Solar Domestic Hot Water

The first heat exchanger, PHX (primary heat exchanger), transfers heat energy in the glycol loop to a local loop of primary water. The glycol loop circulates the mix of water and antifreeze through the collectors and into PHX. The primary water loop circulates water between PHX and the solar installation’s other heat exchangers. PHX is rated at 1.1 MW at $\Delta T = 17^\circ C$ (3.8 MMBtu/hr at $\Delta T = 30^\circ F$), and consists of 99 plates with a heat transfer area of 88 m$^2$ (950 ft$^2$).
A second heat exchanger, AHX (air handling heat exchanger), transfers energy from the primary water loop to a line connected to the building’s existing secondary heating system. It is rated at 1.1 MW at ΔT = 22°C (3.8 MMBtu/hr at ΔT = 40°F). The heat exchanger consists of 121 plates with an heat transfer area of 52 m² (564 ft²). Because the building was originally designed and built to use district energy, it was relatively easy to accommodate the new energy input by simply adding a tee to the existing secondary header.

The third heat exchanger for the solar installation is called DHX (domestic hot water heat exchanger). Domestic hot water applications include bathrooms faucets, showers, and catering needs within the host building. DHX transfers energy from the primary water loop to the building’s domestic hot water system. It is rated at 0.8 MW at ΔT = 50°C (2.7 MMBtu/hr at ΔT = 90°F). The heat exchanger consists of 54 plates with a heat transfer area of 7 m² (76 ft²).

The original mechanical room used a separate domestic hot water heat exchanger, WWH-1, which uses conventional district energy primary water as its source at night or whenever there is not sufficient solar energy. DHX’s discharge is upstream of WWH-1’s intake. As part of the project, the previous WWH-1 was replaced with one identical to DHX.

<table>
<thead>
<tr>
<th>Heat Exchanger</th>
<th>Description</th>
<th>Rating MW (MMBtu/hr)</th>
<th>Delta T °C (°F)</th>
<th>U-value kW/m²K (Btu/hr ft² °F)</th>
<th># of Plates</th>
<th>Heat transf. area m² (ft²)</th>
<th>Fluid 1</th>
<th>Fluid 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHX</td>
<td>Primary</td>
<td>1.1 (3.8)</td>
<td>17 (30)</td>
<td>5.4 (957)</td>
<td>99</td>
<td>88 (950)</td>
<td>Glycol</td>
<td>Primary</td>
</tr>
<tr>
<td>AHX</td>
<td>Air Handling</td>
<td>1.1 (3.8)</td>
<td>22 (40)</td>
<td>7.4 (1,298)</td>
<td>121</td>
<td>52 (564)</td>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>DHX</td>
<td>Domestic</td>
<td>0.8 (2.7)</td>
<td>50 (90)</td>
<td>3.3 (585)</td>
<td>54</td>
<td>7 (76)</td>
<td>Primary</td>
<td>Domestic</td>
</tr>
</tbody>
</table>

Table 8. Heat Exchangers
Pumps

The glycol system uses an 11 kW, 64 m\(^3\)/h @ 40 mwc head (15 HP, 280 gpm @ 130’ head), VFD pump circulating the collector’s heat transfer fluid (P3/P4). Pump speed is varied 50-100% based on calculated solar energy available, and seasonal and variable system set points. This pump has an identical redundant backup.

Circulating the loop of primary water is an 11 kW, 57 m\(^3\)/h @ 42 mwc head (15 HP, 250 gpm @ 136’ head), VFD pump (P1/P2). Its speed is varied 20-100% based on the speed of the glycol loop pump’s speed. This pump also has an identical redundant backup. Between AHX and the tee to the building secondary water header, there is a 5.5 kW, 42 m\(^3\)/h @ 26 mwc head (7.5 HP, 183 gpm @ 85’ head), VFD pump (P5) circulating this solar leg of building secondary water. Its speed is varied 20-100% based on the building’s previously existing automated control system (BAC) secondary water temperature set point. There is no redundant pump as there is sufficient redundancy from the existing secondary system. For the domestic hot water, there is a 0.4 kW, 14 m\(^3\)/h @ 5 mwc head (0.5 HP, 60 gpm @ 15’ head) single-speed pump (P6). There is a similar previously existing pump for WWH-1.

See Figure 59 and Table 9.

Figure 59. Pumps

Table 9. Pumps

<table>
<thead>
<tr>
<th>Pumps</th>
<th>Description</th>
<th>Power kW (HP)</th>
<th>Flow m³/h (gpm)</th>
<th>Head mwc (Ftwc)</th>
<th>VFD / Single</th>
<th>RPM Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1&amp;2</td>
<td>Primary</td>
<td>11 (15)</td>
<td>57 (250)</td>
<td>42 (136)</td>
<td>VFD</td>
<td>20-100%</td>
</tr>
<tr>
<td>P3&amp;4</td>
<td>Glycol</td>
<td>11 (15)</td>
<td>64 (280)</td>
<td>40 (130)</td>
<td>VFD</td>
<td>50-100%</td>
</tr>
<tr>
<td>P5</td>
<td>Secondary</td>
<td>5.5 (7.5)</td>
<td>42 (183)</td>
<td>26 (85)</td>
<td>VFD</td>
<td>20-100%</td>
</tr>
<tr>
<td>P6</td>
<td>Domestic</td>
<td>0.4 (0.5)</td>
<td>14 (60)</td>
<td>5 (15)</td>
<td>Single</td>
<td>100%</td>
</tr>
<tr>
<td>P7</td>
<td>Refill</td>
<td>0.4 (0.5)</td>
<td>14 (20)</td>
<td>5 (50)</td>
<td>Single</td>
<td>100%</td>
</tr>
</tbody>
</table>

Glycol and Primary Water Loop Operation

System controls trigger the pumps on using a pyranometer, and switches to an active mode when the current solar energy available (calculated irradiance reading) exceeds the calculated thermal losses. The trigger value is typically 250-375 W/m² (80 – 120 Btu-hr/ft²) when considering ambient air temperature.

When the system calculates sufficient startup parameters, the glycol pump comes on at minimum speed. A three way valve bypasses PHX until fluid reaches warm up set point. When the glycol reaches its 27°C (80°F) set point, the three way valve allows fluid to PHX and the primary water loop pump comes on at minimum speed. Glycol pump speed modulates based on fluid temperature, its set point and calculated available solar energy. Glycol fluid temperature set point is based on available energy, on-site demand for energy, and seasonal setting.

The glycol loop, export mode (see below) temperature set point is 88°C (190°F) in summer and 93°C (200°F) in winter. The return temperature is nominally up to 17°C (30°F) cooler at full pump speed. This varies with pump speed and thermal load. The set point is a lower value when the system calculates that the building load is more than is being produced. It increases as the system warms up from startup and varies with building secondary loop temperature set point, which varies between 38°C and 85°C (100°F and 185°F). The primary water loop temperature is allowed to vary with load and glycol temperature, and commanded pump speed which is modulated based on glycol pump speed and glycol temperature. See Table 10.
<table>
<thead>
<tr>
<th>Line</th>
<th>Label</th>
<th>Supply Temperatures</th>
<th>Return Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>When</td>
<td>When</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T Enable °C (°F)</td>
<td>T Low °C (°F)</td>
</tr>
<tr>
<td>Glycol</td>
<td>SWS/ SWR</td>
<td>Deliver to PHX</td>
<td>Summer Export</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27 (80)</td>
<td>88 (190)</td>
</tr>
<tr>
<td>Primary water Loop</td>
<td>PWS/ PWR</td>
<td>Start Pumps (P1/P2)</td>
<td>DHX pre heat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27 (80)</td>
<td>27 (80)</td>
</tr>
<tr>
<td>Host building Secondary</td>
<td>HWS/ HWR</td>
<td>Min SP</td>
<td>Min Set Point</td>
</tr>
<tr>
<td></td>
<td></td>
<td>38 (100)</td>
<td>38 (100)</td>
</tr>
<tr>
<td>Domestic</td>
<td>DHWS/ DHWR</td>
<td>Start Pump (P6)</td>
<td>DHX pre heat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27 (80)</td>
<td>27 (80)</td>
</tr>
<tr>
<td>DE Loop Water</td>
<td>DE</td>
<td>Sum/Win Export</td>
<td>Sum Winter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>88/93 (190/200)</td>
<td></td>
</tr>
</tbody>
</table>

*Table 10. St. Paul Solar Installation General Information*
Domestic Hot Water Operation

As the primary water loop warms up, DHX’s domestic water circulation pump comes on and a primary water control valve modulates open. The system is programmed to take advantage of low grade heat prior to reaching elevated temperatures, allowing DHX to preheat the cold water as it passes through for final heating by WWH-1. As the fluid heats further, ultimately the valve is fully open and all of the domestic water is being heated by DHX. As the primary water loop continues to warm above the domestic hot water requirements, the control valve modulates closed, limiting the domestic hot water to its 63°C (146°F) set point. This is several degrees above WWH-1’s 60°C (140°F) set point to avoid unnecessary conventional energy use.

Building Secondary Hot Water Operation

Operation of AHX is in parallel to operation of DHX. As the primary water loop reaches a point at which it can contribute to building secondary heating, the secondary pump for AXH turns on at minimum speed. Meanwhile a control valve on the primary water line modulates open. The building secondary water temperature set point is an input from the building’s existing BAC at a temperature of 38 - 85°C (100 - 185°F). As energy becomes available, the pump speed ramps up. When the secondary set point is being met and the control valve is fully open, it begins to modulate closed to maintain temperature. The operation of AHX is seasonal; it is off in the summer.

District Energy Loop, Export Operation

When the building needs of DHX and AHX are being met and the primary water temperature set point is satisfied, the primary water loop pump’s speed modulates up until the pressure in the line is sufficient to unseat a check valve in the primary water supply line. This is usually at elevated solar irradiance, which is as high as 1,135 W/m² (360 Btu/hr/ft²). The primary water loop and the district energy loop contain the same water and the check valve is what separates the two loops from each other. The district energy loop, which serves most of downtown Saint Paul, supplies heating water to the host building at night and when energy from the sun is not enough. It is normally seated by the pressure from the district energy pumps at the main plant, 1,240 kPa (180 psi). When the local loop pump overcomes the pressure, it exports heated water out to the loop. The export supply temperature varies from summer to winter between 88-93°C (190-200°F). It is lower by the approach temperature of PHX, typically 2 - 3°C (4 –6°F) less than the glycol. The return water from the district energy loop is a year round nominal 70°C (160°F).

District Heating Integration

The piping configuration uses the supply line to export heat to the district energy system, allowing the adaptation of solar thermal to the district energy heating loop without additional piping. An earlier option considered heating the return water and exporting it back to the district energy return line. This would require significant additional piping running through the existing building, requiring significant demolition and subsequent patching. The selected means of return to supply is the best compromise of efficiency, in that it starts with the lower temperature return water, and avoids the construction cost adding a third line to tie to the heating loop. Per basic laws of thermodynamics, the system runs less efficiently at elevated temperatures but district energy compatible export temperatures were a design constraint of the system.
The export of energy from the RiverCentre installation is more efficient in the summer when the district energy loop temperature is lower. Adaptation to a district energy loop that operates at nominally lower temperatures would yield higher efficiency in all conditions.

Given the needs of the system, the specification (Table 11) was written in order to solicit bids from solar manufacturers.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design peak of entire system</td>
<td>289 MW (987 MMBtu/hr)</td>
</tr>
<tr>
<td>Total length of pipe</td>
<td>32,100 m (105,200 ft), supply and return</td>
</tr>
<tr>
<td>Total volume</td>
<td>3,465 m$^3$ (915,000 gallons)</td>
</tr>
<tr>
<td>Design supply temp (winter)</td>
<td>116°C (240°F)</td>
</tr>
<tr>
<td>Design return temp (winter)</td>
<td>71°C (160°F)</td>
</tr>
<tr>
<td>Design supply temp (summer)</td>
<td>82°C (180°F)</td>
</tr>
<tr>
<td>Supply Pressure</td>
<td>1,240 kPa (180 psi)</td>
</tr>
<tr>
<td>Minimum pressure differential</td>
<td>138 kPa (20 psi)</td>
</tr>
<tr>
<td>Reliability rate</td>
<td>99.997 %</td>
</tr>
<tr>
<td>Customer Buildings</td>
<td>196 customer buildings, 298 single family homes</td>
</tr>
</tbody>
</table>

Table 11. District Heating System Specifications

System Expansion, Relief, Containment & Refill

The system includes a 4.5 m³ (1,200 gal.) containment tank sized for all fluid that could drain from the glycol system in an over-pressurization event or scheduled maintenance. It is a horizontal tank, chosen to spread the weight of a full tank over more floor area for structural considerations. The tank is an atmospheric vessel with a vent through the roof. The pressure relief valve in the glycol system is set for 517 kPag (75 psig) and discharging directly into the tank. See Figure 61.

Figure 61. Containment and Expansion Tanks

Adjacent to the containment tank are three 0.5 m³ (130 gal.) diaphragm expansion tanks. These are also horizontal to accommodate structural considerations. They accommodate the volume change of the glycol system that can have fluid temperature vary from -40 to 113°C (-40 to 235°F).

Controls

The system is controlled by a Control Solutions Inc, BACnet device in a collector adjacent to the heat exchangers. It has a small screen for limited display outputs and is connected to an externally accessible site. See Figure 62. Complete control of the system is made possible from this internet accessible connection. The system uses Metasys controls programming.
There are three main control screens used to operate the system. (Examples are given in the following three Figures.) They contain graphic representations of the equipment with various measured values displayed adjacent to the icon. An operator can adjust set points and enter operator overrides to accommodate needs that arise. The programming is also accessible by a system administrator from this site. Most points offer a viewable trend of their recent data. Adjacent to the wall mounted control collector are two BTU meters with displays. One meters the total energy collected by PHX. The other measures the energy exported to the district energy loop. Customer billing is based on subtracting export from the total to get net on site solar energy usage.
Figure 63. PHX Controls Screen
Figure 64. AHX Controls Screen
Figure 65. DHX Controls Screen
O&M Costs

Operation and maintenance costs are relatively limited. Operational complexity is comparable to a commercial domestic hot water heater. To date, expenses have only consisted of washing the collectors and glycol refilling after a minor over-pressurization event. The current budget is $1,000 per year.

Modeling

The design parameters were calculated with a model using 20 years of ASHRAE data for the geographic location. This model considered seasonally calculated irradiance and factors including average ambient weather conditions such as cloud cover and humidity. A similar model utilized by Arcon was used for comparison. This model used more precise historical data over a shorter time period, leaving it vulnerable to statistical skewing from anomalies.

Based on collector selection, District Energy St. Paul worked with its engineering design partners to model expected performance from the Arcon collectors. Initial estimates were based on monthly peaks both in building usage (comprised of space heating and DHW) and in solar production.

System Performance

The following table and figures present the first fourteen months of operating data on solar output of the host building and the solar export to the district energy system.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar TOT MWh / (MMBtu)</th>
<th>Solar Export MWh / (MMBtu)</th>
<th>Estimate Output MWh / (MMBtu)</th>
<th>Estimate Export MWh / (MMBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar, 2011</td>
<td>64 (218)</td>
<td>37 (126)</td>
<td>121 (413)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Apr, 2011</td>
<td>78 (265)</td>
<td>52 (178)</td>
<td>115 (392)</td>
<td>44 (150)</td>
</tr>
<tr>
<td>May, 2011</td>
<td>87 (296)</td>
<td>58 (198)</td>
<td>116 (396)</td>
<td>76 (259)</td>
</tr>
<tr>
<td>Jun, 2011</td>
<td>84 (287)</td>
<td>65 (222)</td>
<td>111 (379)</td>
<td>72 (246)</td>
</tr>
<tr>
<td>Jul, 2011</td>
<td>128 (436)</td>
<td>103 (351)</td>
<td>133 (454)</td>
<td>94 (321)</td>
</tr>
<tr>
<td>Aug, 2011</td>
<td>127 (433)</td>
<td>101 (343)</td>
<td>140 (478)</td>
<td>101 (345)</td>
</tr>
<tr>
<td>Sep, 2011</td>
<td>112 (383)</td>
<td>91 (310)</td>
<td>141 (481)</td>
<td>102 (348)</td>
</tr>
<tr>
<td>Oct, 2011</td>
<td>89 (304)</td>
<td>66 (225)</td>
<td>104 (355)</td>
<td>43 (147)</td>
</tr>
<tr>
<td>Nov, 2011</td>
<td>44 (150)</td>
<td>22 (76)</td>
<td>73 (249)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Dec, 2011</td>
<td>34 (114)</td>
<td>5 (17)</td>
<td>54 (184)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Jan, 2012</td>
<td>32 (110)</td>
<td>8 (29)</td>
<td>71 (242)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Feb, 2012</td>
<td>58 (199)</td>
<td>20 (70)</td>
<td>81 (276)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Mar, 2012</td>
<td>79 (270)</td>
<td>47 (160)</td>
<td>121 (413)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Apr, 2012</td>
<td>108 (368)</td>
<td>78 (266)</td>
<td>115 (392)</td>
<td>44 (150)</td>
</tr>
<tr>
<td>May, 2012</td>
<td>111 (379)</td>
<td>81 (276)</td>
<td>116 (396)</td>
<td>76 (259)</td>
</tr>
<tr>
<td>Total to date</td>
<td>1,235 (4,213)</td>
<td>835 (2,848)</td>
<td>1,612 (5,500)</td>
<td>652 (2,225)</td>
</tr>
<tr>
<td>Last 12 Months</td>
<td>1,006 (3,434)</td>
<td>688 (2347)</td>
<td>1,260 (4,299)</td>
<td>532 (1,815)</td>
</tr>
</tbody>
</table>

Table 12. Monthly Energy Data
Figure 66. Solar Output: Actual & Estimated

Figure 67. Monthly Energy Conventional and Solar (2011)
Economic Analysis

Most conventional businesses evaluate solar installations compared to energy efficiency measures, which appropriately favor investments in energy efficiency. Solar thermal projects can be developed with 10-30 year paybacks, which are more similar to capital investments for HVAC infrastructure (boilers, heat exchangers, etc). Future projects should consider structural advantages, groundstanding systems, and high domestic hot water loads to improve project economics.

Furthermore, return on investment or cost-benefit analysis should be considered with multiple layers of complexity. First, project developers should consider their financial options for developing a solar project. Photovoltaic and thermal projects offer different opportunities for government or utility rebates, tax credits, renewable energy credits, and partnership with 3rd party investors. These all offer the potential to reduce up-front capital investments, but they may also reduce the long-term access to the “free” solar energy or the related marketing if renewable energy credits are exchanged.

Once a capital investment is estimated, the project developers can consider the expected energy generated on an annual basis. Peak demand is a helpful indicator for project size but is only a small part of considering the annual energy generation and overall value of the project. Average annual energy production will indicate both simple and long-term payback. Simple payback for thermal projects traditionally uses current gas prices to value annual energy, which is divided from the capital input to determine payback. A more thorough look at ROI or life-cycle cost analysis would take into account energy forecasts for the thermal source (gas, district heating, etc) and would look at the benefits to extending the life expectancy of redundant equipment, or a similar demand or capacity value. When a thermal energy credit, or other incentive, is added to this equation, it is realistic to draw down the costs below a 20 year payback timeframe.

In addition to technical project economics, there are numerous goodwill-related benefits that promote market transformation. Solar projects offer great opportunities for community tours and education, media coverage, proof of concept and real world showcase of a functioning operational, large-scale installation integrated with district energy. For this project, every decision was made within budget considerations and required thoughtful decisions regarding impacts to other utility operations and their budget needs. Each luxury for the solar project could enhance its performance but needed to be considered based on the value of the performance and the impact on payback time.

Thermal Storage

The ability to tie a solar thermal project to a district heating system offers the effective equivalent of an infinitely sized thermal storage tank. As long as the heating loop is operating; there is no limit to how much energy can be exported. This is crucial because a critical part of a solar thermal system design is storage sizing. Export capability eliminates this constraint. The building used for this installation had a previously existing 3.8 m³ (1000 gallon) domestic storage tank, allowing some additional on-site conventional energy storage. The system can also take advantage of the 4.5 m³ (1,200 gallon) glycol volume and its thermal storage capabilities.
Recommendations for Project Optimization

The following considerations and best practices would be recommended for successful projects:

- Structural vulnerabilities may contribute significant additional costs. Solar projects should be identified prior to construction for optimal savings. Post-construction, projects could be selected based on structural integrity and lowest reinforcement costs. Ideally, groundstanding projects will save the most on capital and engineering if soil conditions and southern exposure are ideal.
- Roof age should be taken into consideration. Solar projects are ideally planned with new construction or a reroofing project.
- Maximum crane access to the installation site minimizes time constraints, planning, and construction costs. The handling and storage of large collectors can also pose a challenge if not considered into site evaluation.
- Ideally, installation should be scheduled between April and October for Midwestern United States climates.
- Future installations should maximize controls integration between existing building controls and additional solar controls. If the systems are well-integrated the conventional system could be programmed to anticipate and to a greater extent accommodate solar energy and maximizing available energy. Metering and controls can be a costly portion of the system and possibilities but investments should be optimized based on the long-term return.
- Instrumentation redundancy and data collection is ideally planned at the onset of a project. A set of commonly needed data points should be determined by all parties involved.
- Ideally, projects with multiple roof installations should target matching elevations to avoid challenges with filling, venting, and isolation.
- Although there are many high-performing international manufacturers, shipping and unloading large collectors can be a challenge. Project developers should identify local offsite delivery points for local pickup and delivery responsibility by the contractor. This can avoid unnecessary delays, and hidden costs associated with import, ocean transport, rail and unplanned storage.
References

1 Lena Sommestad and Erik Larsson, Swedish District Heating Association.
5 Helsinki University of Technology, Improved cogeneration and heat utilisation in DH networks, International Energy Agency Implementing Agreement on District Heating and Cooling including the Integration of CHP, (Annex VIII, Reference #8DHC-08-02).
6 Ekono Energy, Combined heating and cooling; balancing the production and demand in CHP, International Energy Agency Implementing Agreement on District Heating and Cooling including the Integration of CHP, Annex V.
7 PB Power Ltd., A Comparison of distributed CHP/DH with large-scale CHP/DH, Implementing Agreement on District Heating and Cooling including the Integration of CHP, Annex VII.
8 Kleinschmidt, Overview of International Developments in Torrefaction, KEMA Nederland BV.
9 Ormat Inc. website (www.ormat.com).
10 Biodiesel Performance, Costs, and Use, by Anthony Radich. www.eia.gov/oiaf/analysispaper/biodiesel
12 Nexterra Energy Corp.
14 Arcon.
17 Ball State Geothermal Project Enters Stage Two, July 22, 2012,

18 Wei Yang, Experimental performance analysis of a direct-expansion ground source heat pump in Xiangtan, China.


20 Stanford University. Submittal for Global District Energy Climate Award 2013.

21 South East False Creek Energy Center.

22 Direct Contact LLC.


25 Teknikmarknad, Legionellaavdödning och sänkt tappvattentemperatur (Reduced tap water temperatures and increased Legionella protection), 2011.


27 Luftfartsverket.