Innovative Solutions
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Study on Distributed Energy Options in Skaftkärr Testbed

Final report
26.5.2011

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Content

Tiivistelmä

Teknologiavaihtoehdot

Selvityksessä tarkasteltiin paikalliseen energiantuotantoon soveltuvia sähköntuotantoteknologioita, pienimuotoista sähkön ja lämmön yhteistuotantoa sekä energian varastointiratkaisuja. Paikalliseen sähköntuotantoon soveltuvia merkittävimpiä teknologioita ovat aurinkosähkö sekä tuuli- ja vesivoima. Aurinkosähkö soveltuu teknisesti lähes kaikkiin kohteisiin, kunhan aurinkopaneelit voidaan asentaa etelää kohti. Tuulivoiman osalta rajoittavana tekijänä ovat paikalliset tuuliolosuhteet sekä kaupunkimaisessa ympäristössä soveltuvuus ympäröivään maisemaan. Vesivoimaa puolestaan on saatavilla vain harvoissa kohteissa.

Pienimuotoiseen sähkön ja lämmön yhteistuotantoon on olemassa useita teknologioita. Kaasumoottorit ovat eniten käytettyä teknologiaa pienessä kokoluokassa. Mikroturpiinejakin on asennettu moniin kohteisiin viime vuosina. Stirling-moottorit ja polttokennot ovat vielä kehitysvaiheessa, mutta erityisesti polttokennot ovat kiinnostavia, koska niiden sähköntuotannon hyötysuhde (jopa 40–50 %) on erittäin hyvä verrattuna muihin pienimuotoisiin teknologioihin.

Energian varastointiin on myös olemassa useita vaihtoehtoja. Erilaiset akkuteknologiat (esim. Li-ioni ja lyijyakut) soveltuvat hyvin kohteisiin, joissa varastointitarve on tuntien suuruusluokkaa. Lyhyempiin varastointiaikoihin soveltuvat esimerkiksi vauhtipyörät tai superkondensaattorit (sekunteja/minuutteja). Pidempiaikaiseen varastointiin soveltuvat puolestaan erilaiset kemialliset yhdisteet ja pumppuvoimalaitokset. Lämmön varastointiin voidaan käyttää joko vesivaraajia tai faasimuutosaineita.

Tuotantokustannukset

Selvityksessä tarkasteltiin eri teknologioiden tuotantokustannuksia. Koska eri kohteiden sääolosuhteet, kohteiden kokoluokat sekä polttoaineiden hinnat vaihtelevat suuresti, voidaan eri teknologioiden tuotantokustannuksia tarkastella vain suuruusluokan tarkkuudella. Alla olevassa taulukossa on esitetty karkeasti eri teknologioiden tuotantokustannukset sekä pelkän sähkön että kokonaisenergian (sähkö+lämpö) osalta. Kustannuslaskennassa investointeja on tarkasteltu annuiteettimenetelmällä käyttäen 5 % korkokantaa. Polttoaineen hintana on käytetty maakaasun tämän hetkistä pienkuluttajan hintaa (5,4 snt/kWh). Hinnoissa ei ole huomioitu mahdollisia veroja tai tukiaisia.

	Sähkön ja lämmön yhteistuotanto					Sähkö		
	Mikroturpiini	Kaasumoottori	Stirling-moottori	Polttokenno	Höyrukone/turpiini	Aurinkopaneeli	Pientuulivoima	Mikrovesivoima
Sähkön tuotanto (snt/kWh$_e$)	19.0–38.0	17.5–23.0	21.0–43.5	12.5–24.0	18.0–42.0	21.0–36.0	12.0–32.0	8.0–14.0
Energian tuotanto (snt/kWh)	7.5–11.5	9.0–12.0	9.5–15.5	8.0–14.0	9.0–14.5	-	-	-

Yhdistetyn tuotannon osalta huipunkäyttöajaksi on oletettu 5 000 tuntia, aurinkosähkölle 1 000 tuntia (Etelä-Suomi), tuulivoimalle 1 800 tuntia (pientuulivoima rannikolla) ja pienvesivoimalle 4 000 tuntia. Käyttö- ja kunnossapitokustannukset sisältävät huollon ja ylläpidon sekä vakuutukset. Yhdistetyn tuotannon laitteiden eliniäksi on oletettu 15 vuotta. Tuulivoimalan elinikä on 20 vuotta ja aurinkopaneelien ja vesivoimalan 25 vuotta.

Skaftkärriin soveltuvat ratkaisut

Skaftkärriin soveltuvia paikallisia energiaratkaisuja tarkasteltiin kahdessa kokoluokassa, jotka olivat omakotitalo ja 10 talon muodostama taloryhmä. Soveltuvia teknologioita rajoittivat sekä kokoluokka että paikalliset olosuhteet. Tarkastelun tulokset on koottu alla olevaan taulukkoon. Omakotikokoluokka osoittautui liian pieneksi yhdistetyn sähkö ja lämmöntuotannon ratkaisuille. Sähkön tuotannon osalta ainoastaan aurinkopaneelit vaikuttivat soveltuvilta, sillä alueen tuuliolosuhteet eivät ole riittävän hyvät pientuulivoimalle, eikä tuulivoiman katsottu muutenkaan soveltuvan maisemallisesti alueelle. Vesivoimaa ei ollut alueella saatavissa.

	Omakotitalo	Taloryhmä (8-10 taloa)	Asuinalue*
Sähkön ja lämmön yhteistuotanto			
Mikroturpiini		(+)	+
Kaasumoottori		+	+
Stirling-moottori	(+)	+	+
Polttokenno	(+)	+	+
Höyrykone/turpiini			(+)
ORC-voimala			(+)
Sähkö			
Aurinkopaneelit	+	+	+
Pientuulivoima		(+)	+
Mikrovesivoima		(+)	+

*) Ei ollut tarkastelun kohteena

Ratkaisujen kannattavuus

Ratkaisujen kannattavuutta tarkasteltiin sekä omakotitalon että taloryhmän osalta. Omakotitalossa tarkasteltiin järjestelmää, jossa oli aurinkopaneelit, jotka tuottivat 50 % sähköntarpeesta. Sähkön varastona toimi sähköauton akku. Lisäksi tarkasteltiin optiona ratkaisua, jossa oli myös paikallinen talossa sijaitseva akusto. Taloryhmän osalta tarkasteltiin ratkaisua, jossa oli kaasumoottoriin perustuva sähkön ja lämmön yhteistuotantoyksikkö sekä iso vesivaraaja lämmön varastointiin ja akusto sähkön varastointiin. Lisäksi tarkasteltiin optiota, jossa oli mukana myös aurinkopaneelit, jotka oli mitoitettu tuottamaan 20 % tarvittavasta sähköstä.

Tarkastelut osoittivat, että ilman tukiaisia on vaikea saavuttaa taloudellista kannattavuutta, etenkin pienemmässä kokoluokassa. Suuremmassa kokoluokassa kannattavuus oli hieman parempi, vaikkakin aurinkopaneelien lisääminen taloryhmään ei ollut kannattavaa. Yleisemmin voidaan todeta, että tuet ja työkustannusten minimointi aurinkosähköjärjestelmien asentamisessa ovat avainasemassa järjestelmien kannattavuuden kannalta. Mikäli asennuskustannuksia voitaisiin alentaa järkevällä rakennusintegraatiolla, voitaisiin päästä selvästi parempaan kannattavuuteen etenkin talokohtaisissa ratkaisuissa.

Kotimaiset toimijat

Työssä selvitettiin myös eri teknologioihin liittyvät kotimaiset toimijat painottaen niitä teknologioita, jotka olivat Skaftkärriin soveltuvia. Selvityksen perusteella eri teknologioille löytyy kohtuullisesti toimittajia, vaikka määrät ovat vähäisiä johtuen markkinoiden pienuudesta. Koska useat teknologiat ovat vielä kehitysasteella, ovat monet toimijat keskittyneet vielä tuotekehitykseen. Tulevaisuudessa uudet asuinalueet ja älykkäiden sähköverkkoratkaisujen yleistyessä myös pienen kokoluokan ratkaisujen oletetaan yleistyvän ja toimijoiden määrän kasvavan.

1 Introduction

In the distributed energy production model electricity or heat is produced near the end-user in relatively small units - using very often local renewable energy sources. These are e.g. solar thermal or photovoltaic applications, wind power, fuel cells or other small-scale CHP technologies using e.g. bio-based fuels.

Locally produced intermittent renewable electricity can be optimized by storing produced electricity and using it when electricity price is high. Electricity storage is an important part of smart grid development from the perspective of supply-demand flexibility. Heat can be stored as well using e.g. water tank placed either under or above the ground.

Distributed energy production technologies are already utilized in domestic residential areas and the trend is emerging. Designing and planning needs to be emphasized in order to build and maintain technically and economically sustainable energy system.

The objective of this study is to present the possibilities of distributed energy production and storage technologies. The study highlights available technologies and services of distributed energy production and helps to build up a testbed solution that could lead to demonstration-scale application in near future. This testbed is a part of developing process of Skaftkärr area where energy efficiency and environmental issues are emphasized.

In this report, feasible[1] production and storage technologies are presented in Chapter 2. Chapter 3 introduces economical characteristics of studied technologies. Chapter 4 points out suitable technologies for Skaftkärr area and presents profitability analysis of these technologies via two cases. Domestic actors[2] in technology value chains are also presented in Chapter 4. Chapter 5 summarizes the study and its findings.

2 Production Technologies

2.1 Combined Heat and Power (CHP)

2.1.1 Microturbine

Typically microturbine refers to gas turbine which power output ranges from less than a kilowatt to tens or hundreds of kilowatts. Size range in this study is 15–500 kW_e[3]. Microturbine includes

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[1] Refers to technologies that are mature or nearly mature for commercial-scale applications.

[2] Manufacturers, suppliers/importers and service providers related to technologies that are feasible in Skaftkärr area.

[3] kW_e refers to electricity production (e = electricity). Abbreviation for thermal energy is *th* (kW_{th}).

generator, single stage radial compressor and single stage radial turbine that are fitted to the shaft using either oil or air bearings. Air is pressurized in compressor before feeding it into combustion chamber. Recuperator, which enables utilization of hot exhaust gases, improves efficiency of the process[4]. Commonly mentioned advantages of microturbines compared to other technologies for small-scale energy production include: small number of moving parts, compact size, lightweight, greater efficiency, lower emissions and electricity costs, and opportunities to utilize waste fuels.

Turbine efficiency is strongly related to power output. In the smallest unrecuperated applications the electrical efficiency is around 15 %. In larger scale the electrical efficiency can reach 30 %, if recuperator is used. Unrecuperated microturbines have lower efficiencies but also lower capital costs, higher reliability, and more heat available for CHP applications than recuperated units. With heat recovery (CHP applications) the overall efficiency is up to 85 %. (NIBS 2011)

Microturbines are fuel-flexible and both gaseous and liquid fuels are used. The most commonly used fuels are natural gas, biogas, hydrogen and diesel oil. Waste gas, liquefied petroleum gas (LPG), gasoline, methanol and ethanol are suitable as well. Process scheme of microturbine is presented in Figure 1.

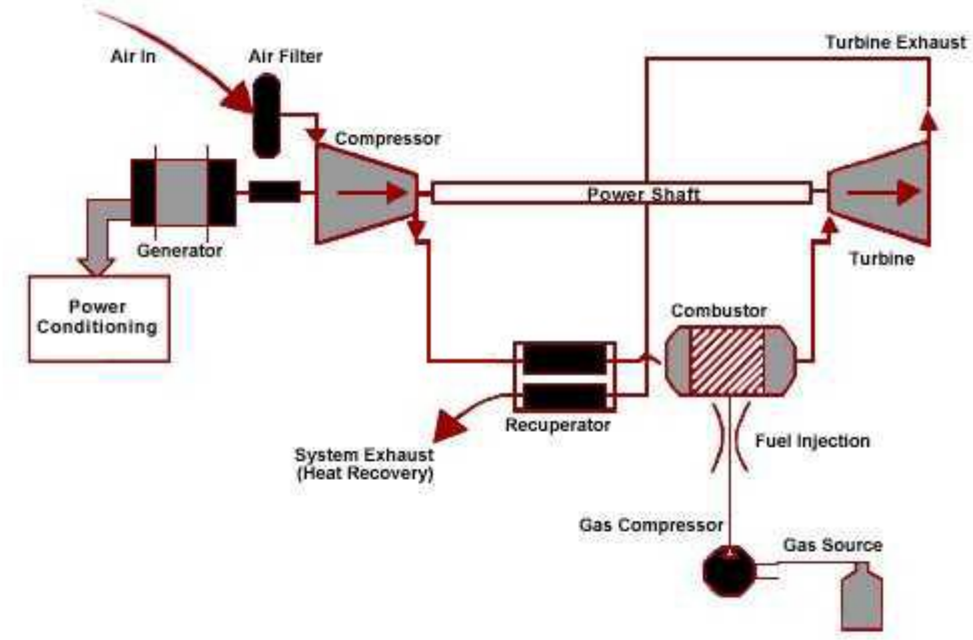

Figure 1. *Microturbine process scheme including heat recovery. (CEC 2011)*

Microturbine capital costs range from 500–800 euros per kW_e. These costs include all hardware, associated manuals, software and initial training. Adding heat recovery (CHP) increases the cost 50–250 euros per kW_e. Installation costs vary significantly by location but generally add 30–50 % to the total investment cost. Operation and maintenance costs range from 0.3–1.2 cents per kWh electricity produced. (NIBS 2011) Economies of scale apply and therefore larger applications

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[4] Heat exchanger recovers some of the heat from an exhaust stream and transfers it to the incoming air stream, boosting the temperature of the air stream supplied to the combustor.

generally lower the relative costs. Technical and economical characteristics of microturbines in selected scale are presented in Table 1.

Microturbines are suitable for applications that use high-temperature air or steam, i.e. industrial applications. Residential applications are not common since the power output of the turbine is typically too high and using only part of the available capacity is uneconomical. Nor the fluctuating load profile of residential buildings support microturbine use.

***Table 1**. Technical and economical characteristics of microturbines (NIBS 2011; Vartiainen et al. 2002)*

Technical	
Size range (kW$_e$)	15–500
Electrical efficiency (%)	15–30
CHP efficiency (%)	70–85
Heat temperature, steam (°C)*	50–80
Maintenance interval (h)	5,000–8,000
Economical	
Capital cost (€/kW$_e$) (with heat recovery)	500–800 (550–1,050)
O&M (c/kWh$_e$)	0.3–1.2
Production cost (c/kWh)**	
- electricity	19.0–38.0
- CHP	7.5–11.0

*) Exhaust air temperature varies between 250–300 °C.

**) For alleged lifetime of 15 years.

2.1.2 Gas Engine

Gas engine application consists of piston engine and generator attached to it. Size range in this study is 10–200 kW, yet there are engines with power output of up to 20 MW. Small-size engine technology is typically based on diesel engines where spark ignition is added. Engine efficiency correlates with power output; thus more powerful engine usually has higher efficiency. Electrical efficiency in the size range of this study is 30–35 %. In cogeneration the excess process heat is utilized to produce hot water (or low-pressure steam[5]) addition to electricity, in which case the overall (CHP) efficiency can be up to 85 %.

Gas engine can be designed to run on gaseous fuels (natural gas, biogas, industrial waste gas, LPG) or liquid diesel fuel. Mixture of the two can also be used. When running on gaseous fuels spark ignition is used; with liquefied fuels engine uses compression ignition. Gaseous fuels are typically used in sustained CHP applications; diesel is more common as a backup system fuel but can also be used in cogeneration if gas is not available. Figure 2 illustrates profile of the gas engine.

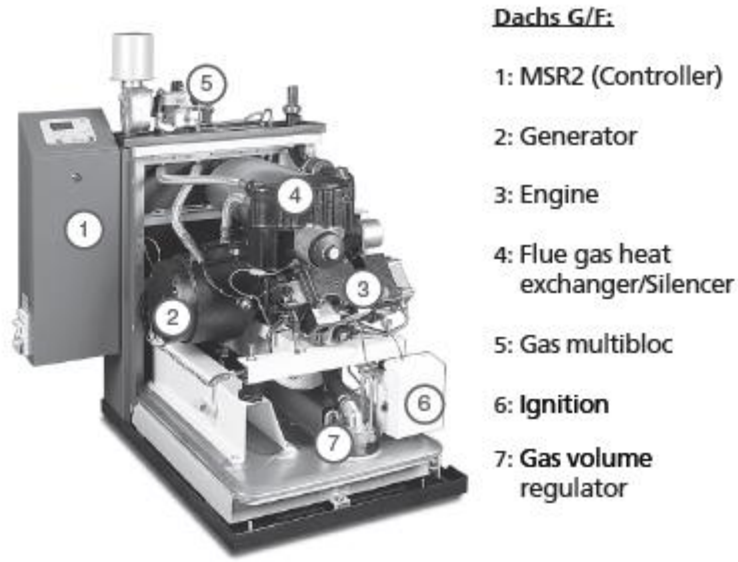

Figure 2. *Gas engine profile. (Senertec 2011)*

Gas engine capital costs range from 800–1,000 euros per kW_e. These costs include all the necessary equipment and peripheral devices. Adding heat recovery (CHP) increases the cost 50–150 euros per kW_e. Installation costs vary significantly by location but are generally 450–650 euros per kW_e.

Maintenance costs vary with type, speed, size and numbers of cylinders of an engine. Maintenance comprised of routine short interval inspections/adjustments and periodic replacement of engine oil and filter, coolant and spark plugs (typically 500–2,000 hours). An oil analysis is part of most preventative maintenance programs to monitor engine wear. Minor overhaul is generally recommended between 8,000 and 30,000 hours of operation that entails a cylinder head and turbocharger rebuild. A major overhaul is performed after 30,000–72,000 hours of operation and involves piston/liner replacement, crankshaft inspection, bearings and seals. Operation and maintenance costs range from 1.0–3.0 cents per kWh electricity produced. (EPA 2008a) Larger-size applications generally lower the relative investment costs and peripheral devices' share from overall investment costs declines (Vartiainen et al. 2002). Technical and economical characteristics of gas engines in selected scale are presented in Table 2.

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[5] Steam is not produced in the size range of this study.

Gas engines suit best for the applications which have a moderate and stable demand for electricity and heat. In the smallest-scale (single house) applications the need for comprehensive overhaul and arising noise reduces willingness to invest to this technology. Advantages come forward in larger-scale applications, such as groups of several houses or in industrial applications.

***Table 2**. Technical and economical characteristics of gas engines (EPA 2008a; Vartiainen et al. 2002)*

Technical	
Size range (kW_e)	5–200
Electrical efficiency (%)	30–35
CHP efficiency (%)	75–85
Heat temperature (°C)*	85–100
Maintenance interval (h)**	8,000–30,000
Technical availability (%)	95
Engine speed (rpm)	1,000–3,000
Economical	
Capital cost (€/kW_e) (with heat recovery)	800–1,000 (850–1,150)
O&M (c/kWh_e)	1.0–3.0
Production cost (c/kWh)*** - electricity - CHP	 17.5–23.0 9.0–12.0

*) Exhaust air temperature varies between 450-570 °C.

**) Refers to minor overhaul.

***) For alleged lifetime of 15 years.

2.1.3 Stirling Engine

Stirling engine is an external combustion engine, thus it differs from Otto and diesel engines, which are based on internal combustion. Hence the cylinder space of Stirling motor is closed and combustion process takes place outside the cylinders. The general cycle consists of compressing cool gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle, i.e. piston moves back and forth due to change in pressure. The working gas used in Stirling engine is typically helium or nitrogen. External heat production makes it possible to use various fuels, e.g.

natural gas, oil or biomass. Current development focus is on solar[6] and waste-heat applications. Size range in this study is 1–25 kW.

Commonly mentioned advantages of Stirling engines compared to Otto and diesel engines are lower emissions and level of noise. Because of external combustion the maintenance interval is longer, which lowers the O&M costs especially in small size range (< 30 kW), wherein Stirling technology is able to compete with gas engines. (Vartiainen et al. 2002)

Electrical efficiency in the size range of this study is 15–30 %. Efficiency depends on fuel: in natural gas applications efficiency can be 25–30 %, and with solid fuels (e.g. biomass) the efficiency is typically less than 20 %. In cogeneration the overall (CHP) efficiency is 75–90 %. (WADE 2011; Vartiainen et al. 2002) Simplified structure of Stirling engine is presented in Figure 3.

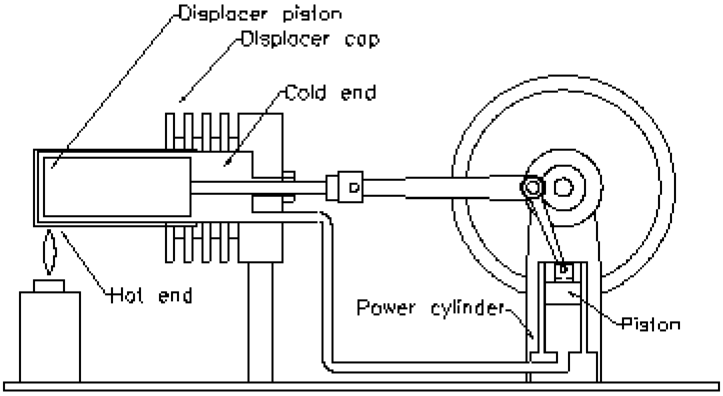

Figure 3. *Stirling engine structure. (PES 2011)*

Commercial applications of Stirling engines have limited availability and accurate cost data is hard to find. Capital costs range is estimated to be 1,400–3,000 euros per kW_e. These costs include heat exchanger, which typically accounts for 40 % of the total engine cost. Operation and maintenance costs have high uncertainty. Albeit Stirling engines need less comprehensive overhaul than the combustion engines the O&M costs per produced electricity are high. Technical and economical characteristics of Stirling engines are presented in Table 3.

Stirling engines are suitable for residential or portable applications. The small size and quiet operation mean that they would integrate well into a domestic environment. Applications suitable for larger than residential scale are not available nor under development.

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[6] There is the possibility of using a solar dish to heat the Stirling engine eradicating the need for combustion of a fuel.

***Table 3**. Technical and economical characteristics of Stirling engines (WADE 2011; Vartiainen et al. 2002)*

Technical	
Size range (kW_e)	1–25
Electrical efficiency (%)	15–30
CHP efficiency (%)	75–90
Heat temperature (°C)	60–80
Maintenance interval (h)	4,000–6,000
Engine speed (rpm)	1,500–1,800
Economical	
Capital cost (€/kW_e)*	1,400–3,000
O&M (c/kWh_e)	1.0–2.5
Production cost (c/kWh)**	
- electricity	21.0–43.5
- CHP	9.5–15.5

*) Includes heat recovery.

**) For alleged lifetime of 15 years.

2.1.4 Steam Engine and Steam Turbine

Steam engines are typically external combustion engines, so the production method is similar to Stirling engines. This makes possible to use external heat sources such as solar heat or geothermal energy. The heat cycle is known as the Rankine cycle. The water turns to high pressure steam in a boiler and expands greatly in volume, and can be used to generate mechanical power, usually via pistons[7] or turbines that are linked to engine shaft. The pressure drops and steam is condensed and pumped back into the boiler. The low pressure steam can be further used to produce heat.

The steam is produced in separate boiler, which enables flexible fuel use. Today steam turbines have in practice displaced steam engines in energy production because turbines are proved to be more efficient. Steam turbine is the most common method to generate electricity in large centralized

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[7] Usually steam engines have several different size cylinders instead of one.

power plants wherein the electrical efficiency can top 40 % (when using steam re-heater and economizer the efficiency can reach almost 50 %). In the size range of this study (50–3,000 kW$_e$) the electrical efficiency is typically between 15 and 35 %. (Vartiainen et al. 2002) The overall efficiency (CHP) in this size range is 75–85 %.

CHP application based on combination of boiler and steam engine the released thermal energy is used to produce steam in boiler. The steam is then led to steam engine that runs electric generator. In smaller than 1 MW$_e$ applications steam engine is more economical compared to steam turbine, because turbine efficiency decreases when downscaled. Steam turbine is recommended when the electrical output demand exceeds 1 MW$_e$.

Steam engines and steam turbines can utilize almost every solid, liquid or gaseous fuel – fossil or renewable. Common fuels are coal, peat, recovered fuels (REF) and biomass. Choice of the boiler defines how moist fuels can be used. Some *grate boilers* take fuels with moisture level of over 60 %, yet dried fuels ensure better efficiency of the process. Working principle of steam engine and simplified process scheme of steam turbine are presented in Figure 4.

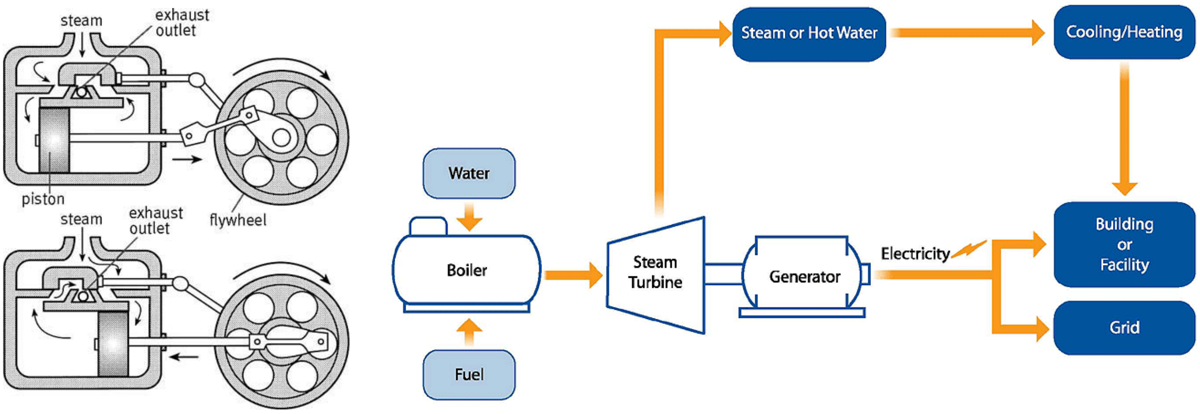

Figure 4. *Working principle of steam engine (left) and process scheme of steam turbine (right). (YD 2011; EPA 2011)*

A steam turbine-based CHP plant is a complex process with many interrelated subsystems that must usually be custom designed. A typical breakdown of installed costs for a steam turbine CHP plant is 25 % - boiler, 25 % - fuel handling, storage and preparation system, 20 % - stack gas cleanup and pollution controls, 15 % - steam turbine generator, and 15 % - field construction and plant engineering. Typical complete plant costs run upwards of 1,300–3,000 euros per kW$_e$. Steam turbine maintenance costs are quite low, typically around 0.3–1.0 euros per kWh electricity produced.

Compared to steam turbines, costs for steam engine applications are generally higher and significantly site specific. (EPA 2008b; Vartiainen et al. 2002) Technical and economical characteristics of steam engines and steam turbines are presented in Table 4.

Steam engines and steam turbines are suitable for industrial applications and district heating. Residential scale applications are basically not viable.

***Table 4**. Technical and economical characteristics of steam engines and steam turbines (EPA 2008b; WADE 2011; Vartiainen et al. 2002)*

Technical	
Size range (kW_e)	50–3,000
Electrical efficiency (%)	15–35
CHP efficiency (%)	70–85
Economical	
Capital cost (€/kW_e)*	1,300–3,000
O&M (c/kWh_e)	0.3–1.0
Production cost (c/kWh)**	
- electricity	18.0–42.0
- CHP	9.0–14.5

*) CHP plant investment cost. Minimum value refers to large steam turbine application and maximum value to small-scale steam engine application.

**) For alleged lifetime of 15 years.

2.1.5 Fuel Cell

Fuel cell converts chemical energy of the fuel into electricity. Most commonly used fuel is hydrogen, which can be produced e.g. from natural gas or methanol by reformation. Yet many combinations of fuels (hydrocarbons and alcohols) are possible. Oxygen, which is usually segregated from air, is typically used as fuel cell's oxidant. Other oxidants include chlorine and chlorine dioxide.

The fuel is fed to one electrode and oxidant to other. When the fuel enters a fuel cell, a catalyst on the anode separates hydrogen ions and electrons from the fuel. Negatively charged electrons flow through an external load to the cathode generating electricity, whilst the hydrogen ions pass through the electrolyte to the cathode, where they combine with oxygen and the electron to produce water and release thermal energy. The voltage produced by a single fuel cell is small. However, fuel cells can be organized into stacks to provide power as required. Fuel cells are thus an ideal modular technology. The power output range in this study is 1–1,000 kW.

Fuel cells fall into two categories: low-temperature and high-temperature. This study concentrates on proton exchange membrane fuel cells (PEMFC), which is a low-temperature technology, and molten carbonate fuel cells (MCFC) together with solid oxide fuel cells (SOFC), which represent a high-temperature technology. Low-temperature fuel cells have been around for decades, and are therefore more reliable technologies although they are still under development and demonstration phase. High-temperature fuel cells are emerging technologies with some commercial experience. (WADE 2011; Vartiainen et al. 2002)

Major advantage of fuels cells is a high efficiency. Yet the fuel reform lowers the efficiency in the small-scale low-temperature applications. Fuel cells electrical efficiency can reach 55 %; when used for cogeneration (CHP) the overall efficiency ranges from 75–95 %. Figure 5 illustrates the simplified fuel cell process scheme.

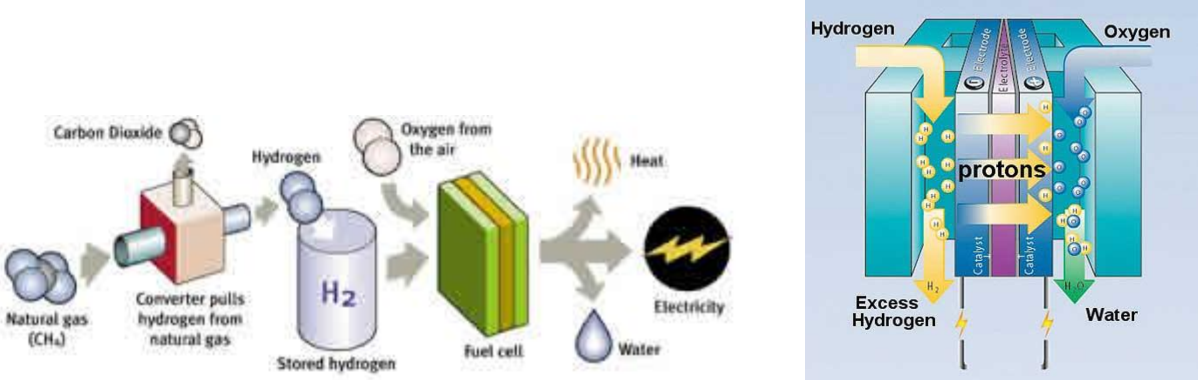

Figure 5. *Fuel cell process scheme. (HCL 2011; WKSU 2011)*

The current installed capital costs of a fuel cell are relatively high, due to the materials used and lack of mass-production. There have been significant and continuing reductions in the cost of balance of plant, and in production costs of the fuel cells. O&M costs, lifetimes and availabilities for fuel cells remain somewhat speculative, due to lack of operational experience. Technical and average economical characteristics of fuel cells engines are presented in Table 5.

Technically fuel cells are viable in several applications because high efficiencies can be reached even when used only part of the available capacity. Low-temperature fuel cells, such as PEMFC, are the most suitable for single house applications. High-temperature fuel cells, such as MCFC and SOFC, are typically designed for industrial or district/areal heating applications where higher-temperature heat is needed. (Vartiainen et al. 2002)

Table 5*. Technical and economical characteristics of fuel cells (DOE 2011; WADE 2011)*

	PEMFC	**MCFC**	**SOFC**
Technical			
Size range (kW)*	1–100	250–1,000	5–1,000
Electrical efficiency (%)**	30–35	40–45	45–50
CHP efficiency (%)	75–85	85–95	85–95
Working temperature (^{o}C)	50–100	600–700	600–1,000
Fuel type	hydrogen, natural gas	hydrogen, natural gas	hydrogen, natural gas, carbon monoxide
Technical availability (%)	95–99		

Economical	
Capital cost (€/kW$_e$)***	1,000–2,700
O&M (c/kWh$_e$)	0.3–1.5
Production cost (c/kWh)****	
- electricity	12.5–24.0
- CHP	8.0–14.0

*) Typical power output range; build from modules.

**) For natural gas (incl. reforming), efficiency is higher when using hydrogen.

***) Target price for commercial products. Includes heat recovery.

****) For alleged lifetime of 15 years.

2.1.6 Organic Rankine Cycle (ORC)

The organic Rankine cycle involves the same components as in a conventional steam power plant (a boiler, a work-producing expansion device, a condenser and a pump)[8]. ORC uses an organic mass fluid with a liquid-to-vapor phase change, or boiling point, occurring at a lower temperature than the water-to-steam phase change. Refrigerants and hydrocarbons such as *R123*, *n-pentane* and *toluene* are commonly used fluid components that allow Rankine cycle heat recovery from lower temperature sources such as biomass combustion, industrial waste heat, geothermal heat or solar heat. ORC working fluids for geothermal and solar heat applications typically have evaporation temperature of 60–150 °C and condensing temperature of 20–35 °C. Values for power plant ORC working fluids are higher.

Local generation leads to smaller scale power plants (< 1 MWe), which excludes traditional steam cycles that are not cost-effective in this power range. The efficiency of the ORC is relatively low as a result of the lower temperature range. Yet this can be worthwhile because of the lower cost involved in gathering heat at lower temperature.

ORC seems to be a promising technology in concentrating solar power in a view to decrease plant size and investment costs. Solar plants can work at lower temperatures, and the total installed power can be reduced down to the kilowatt scale. Secondly, in great part of industrial flue gases temperature varies between 100 and 300 °C. For economical reasons traditional steam cycles wouldn't allow recovering heat in this temperature range, in contrast to ORC. (Quoilin&Lemort 2009) The costs of ORC vary significantly depending on the application in question.

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[8] In Rankine cycle the working fluid is pumped to a boiler where it is evaporated, passes through a turbine and is finally re-condensed.

2.2 Electricity Production

2.2.1 Photovoltaics (PV)

Photovoltaics generate electrical power by converting solar radiation into electricity using solar panels. An inverter is needed to transform the generated direct current (DC) electricity into alternating current (AC) electricity.

Availability of solar energy depends mainly on local latitude and weather conditions. In Finland the annual radiation to horizontal surface is 940 kWh/m^2 on average in Helsinki. In Jyväskylä the value is roughly 880 kWh/m^2 and in Sodankylä 790 kWh/m^2. If the panels are directed optimally the yield can reach 1 160 kWh/m^2 in Southern Finland. (Vartiainen 2000)

PV system is typically composed of several solar panels that can be connected in parallel, series connection is also possible. Typical PV system for residential application is in power range of 1–3 kW. The power output range in this study is 0.5–50 kW$_p$[9]. A rule of thumb is that in Finland one kW of installed capacity produces roughly 1,000 kWh electricity.

Addition to available solar radiation, qualitative characteristics of PV system play a major role in efficient electricity production. Commercially available solar panels' efficiency varies between 10 and 15 %. Use of batteries (to store the energy) and inverter lowers the overall efficiency. The most common panel material today is crystalline silicon, which has the highest efficiency within commercially available technologies. Other materials presently used include amorphous silicon, cadmium telluride, and copper indium selenide/sulfide.

Solar panels are nearly maintenance-free because panels do not erode easily and the system does not include moving parts. Many PV suppliers give their products even a 25-year technical warranty and the lifetime for panels is estimated to be around 30–50 years. (Pesola et al. 2010) Working principle of PV system is presented in Figure 6.

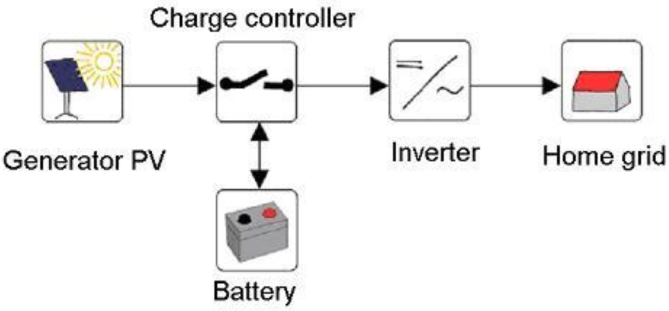

Figure 6. *Working principle of photovoltaics system. (PVS 2011)*

Economies of scale apply also for solar power and therefore larger applications generally lower the relative costs. The costs of solar power systems dropped notably in 2010, mostly because PV

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[9] Watt-peak (W$_p$) is a measure of the nominal power of a photovoltaic solar energy device under laboratory illumination conditions.

installations have accumulated rapidly. Today the overall PV system costs, including installation, are 3,000–5,000 euros per kW_p on average. A typical breakdown of overall costs for PV system is 35 % - PV module, 15 % - inverter and 50 % - labor. (ASES 2011; Photon 2011) Technical and economical characteristics of photovoltaics are presented in Table 6.

PV technology develops fast and solar power systems are to become a cost-effective electricity production form for urban environment. Technology is noise-free and suitable to be integrated into residential buildings' rooftops and other outdoor applications.

***Table 6**. Technical and economical characteristics of photovoltaics (DOE 2011; Photon 2011; Vartiainen et al. 2002)*

Technical	
Size range (kW_p)	0,5–50
Annual operation (hours)	900–1,100
Panel yield (kWh_e/m^2)	80–120
Economical	
Capital cost (€/kW_p)*	3,000–5,000
O&M (c/kWh_e)	0.1–0.5
Production cost (c/kWh_e)**	21.0–36.0

*) Investment cost (incl. equipment, labor etc.).

**) For alleged lifetime of 25 years.

2.2.2 Small-scale Wind Power

In Finnish coastline and skerries wind power plants have annual operational time of 1,800–2,500 hours. Operational hours can reach 3,000 in fells and offshore. Inland operational hours usually remain under 1,500. Average annual efficiency depends on how well the wind power station is optimized in its location. The statistical distribution and time-dependent fluctuations of wind speed are important to determine before realizing the wind power investment.

The small-scale vertical-axis wind power applications typically have the electricity output of 20 kW tops. The horizontal-axis applications' power range starts from few hundred watts; these are seldom used because generally comparative costs rise when the output level drops. Turbines with power output of less than 10 kW are called microturbines. The tower is usually 5–45 meters high and the rotor diameter is between 4 and 14 meters. (Pesola et al. 2010) Working principle of small-scale wind power system is presented in Figure 7.

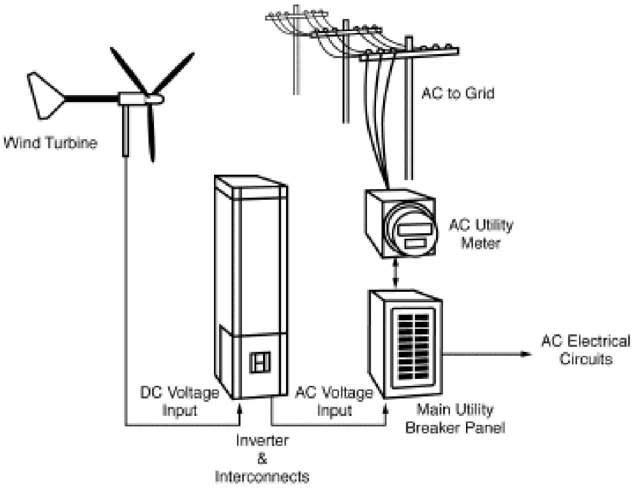

Figure 7. *Working principle of small-scale wind power system. (GoGreenSolar 2011)*

Small-scale wind power plant starts generating electricity when the wind speed reaches 2–3 m/s. Nominal wind speed is typically 8–12 m/s. (Eagle 2011) Small-scale wind power is a practical alternative or addition to PV applications. The unit cost of investment is just about equal to PV applications but wind turbine generates electricity round the clock if located properly, unlike solar power which is dependent on available sunlight. (Pesola et al. 2010) Yet small-scale wind power has relatively high unit costs and larger applications generally lower the relative costs (€/kW). Technical and economical characteristics of small-scale wind power are presented in Table 7.

The latest (small-scale) models have become more compact, less noisy and more aesthetic and they are now being deployed in urban environments including residential areas on rooftops or localities.

Table 7*. Technical and economical characteristics of small-scale wind power (WEF 2011; STY 2011)*

Technical	
Size range (kW_e)	0,5–20
Annual operation (hours)	1,300–2,500
Technical availability (%)	95–99
Economical	
Capital cost (€/kW_e)*	2,000–6,000
O&M (c/kWh_e)	3.0–5.0
Production cost (c/kWh_e)**	12.0–32.0

*) Investment cost (incl. equipment, labor, training etc.).

**) For alleged lifetime of 20 years.

2.2.3 Micro-scale Hydro Power

Hydro power can be divided into three categories: large-scale, small-scale and micro-scale. Statistics Finland *(Tilastokeskus)* defines that micro-scale refers to hydro power plants with power output less than 1 MW. The power range in this study is 20–250 kW_e. Potential unutilized locations for micro-scale hydro power plants are estimated to be around 350 in Finland (Motiva 2011).

Hydro power plant's efficiency depends partly on used technology. Horizontal-axis tube turbine (Kaplan) is the most commonly used model that has efficiency typically up to 90 %, which enables the overall plant efficiency of 75–85 %. The high efficiency originates from good adjusting qualities of the Kaplan technology.

Hydro power is a capital-intensive technology, which means that as in wind power the production costs are mainly comprised of investment and finance expenditures. Larger hydro power applications lower the relative costs, and rule of thumb is that the unit cost of investment rise rapidly when moving to applications smaller than 300 kW. Working principle of micro-scale hydro power system is presented in Figure 8.

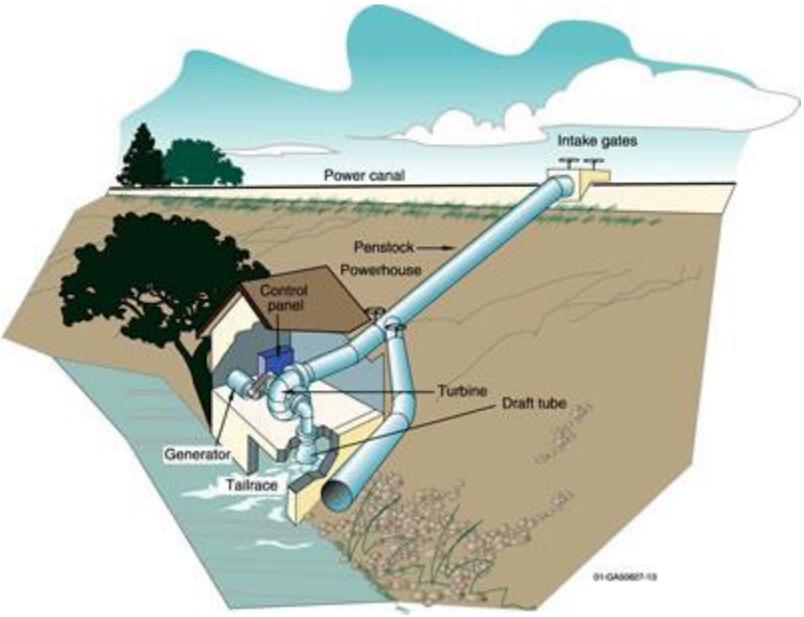

Figure 8. *One possibility to utilize hydro power in micro-scale. (GENI 2011)*

Typical micro-scale hydro power investment costs were between 4,000 and 7,000 euros per kW_e in 2008. A typical breakdown of installed costs for hydro power plant is 20 % - dam and canals, 15 % - machine hall and structures, 35 % - mechanical devices, generator, automation and electrification. Additional costs arise from environmental protection, land property acquisition etc. O&M cost for hydro power plants smaller than 1 MW are estimated to be 0.8–1.2 cents per kWh electricity produced. Operation accounts for 60 % and maintenance 40 % of this on average. (Pienvesivoimayhdistys 2009) Technical and economical characteristics of micro-scale hydro power are presented in Table 8.

New micro-scale hydro power applications can be utilized in unprotected waters. Technology is naturally very place-specific and viable applications are usually old mills, dams or plants that need replacement.

Table 8*. Technical and economical characteristics of micro-scale hydro power (Pienvesivoimayhdistys 2009; Vartiainen et al. 2002)*

Technical	
Size range (kW_e)	20–250
Overall efficiency (%)	75–85
Annual operation (hours)	4,000–5,000
Economical	
Capital cost (€/kW_e)*	4,000–7,000
O&M (c/kWh_e)	0.8–1.2
Production cost (c/kWh_e)**	8.0–14.0

*) Investment cost (incl. equipment, labor, dam and peripheral).

**) For alleged lifetime of 25 years.

3 Energy Storage Technologies

3.1 Electricity Storage

3.1.1 Battery

Electricity storage in batteries is based on reversible chemical reactions (rechargeable batteries). There are several basic systems commercially available today: lead acid, NiCd (nickel cadmium), NiMH (nickel metal hydride), NiZn (nickel zinc), Li-ion (lithium ion), ZnBr (zinc bromide), NaS (sodium sulfur) and VR or VRB (vanadium redox battery). The last two systems belong to the so called flow batteries where the electrolyte or electrode is liquid and flows during charge or discharge. Some of the mentioned systems are not single systems, but contain two or more varieties, such NiMH and Li-ion. In addition, other systems, e.g. metal-air and many others are under development, and thus not commercially viable yet.

Different battery types have different characteristics and most suitable application areas which are illustrated at the end of this chapter (comparison of electricity storage technologies). Today the main driver of battery development is the automotive industry.

Electric vehicles

Electric vehicles can be categorized e.g. in micro-hybrids, hybrids (HEV) and full electric vehicles (EV). The role of the battery increases, respectively.

Micro-hybrids – conventional cars with automatic start-stop technology – are the simplest automotive hybrid system and one of the most cost-effective ways to improve fuel economy and reduce automotive carbon emissions. In a micro-hybrid, the engine shuts off when the vehicle is stopped, providing a 5 to 8 % improvement in overall fuel economy (even higher in city-only driving) at a cost under 350 euros per vehicle. Micro-hybrid technology will be deployed as standard equipment in millions of vehicles in Europe, Asia and North America over the next several years. (PowerGenix Batteries 2011)

Batteries in HEVs are bigger than in micro-hybrids, give also cruising power and use regenerative braking systems to charge the battery. Full EVs rely totally on batteries as their power source.

The batteries of electric cars should have the following characteristics:

1) Store as much energy as possible in a given volume to achieve a long operating range
2) Have the lowest weight possible to reduce the load on the drive system
3) Recharge rapidly and easily
4) Perform well through many charge/discharge cycles over the life of the vehicle

Electric cars – and especially batteries for them – are developed intensively by many car manufacturers as well as universities to achieve comparable performance and convenience to present cars. The target is very demanding and so far, it has been unachievable, in general terms. But there are special applications, where HEVs and to some extent, EVs, can already be competitive, e.g. forklifts and alike, as well as short range vehicles, such as taxis and waste collection vehicles.

3.1.2 Supercapacitor

Supercapacitor or ultracapacitor or supercondenser is more accurately termed as electric double-layer capacitor (EDLC) or electrochemical (EC) capacitor.

Electrochemical capacitors (EC) store electrical energy in the two series capacitors of the electric double layer (EDL), which is formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is nanometers. The capacitance and energy density of these devices is thousands of times larger than electrolytic capacitors.

The electrodes are often made with porous carbon material. The electrolyte is either aqueous or organic. The aqueous capacitors have a lower energy density due to a lower cell voltage but are less expensive and work in a wider temperature range. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones and have lower leakage current.

Compared to lead-acid batteries, EC capacitors have lower energy density but they can be cycled tens of thousands of times and are much more powerful than batteries (fast charge and discharge capability). While the small electrochemical capacitors are well developed, the larger units with energy densities over 20 kWh/m^3 are still under development. (ESA 2011)

Figure 9 shows comparison of energy and power densities together with charge/discharge time scale of different electricity storage technologies.

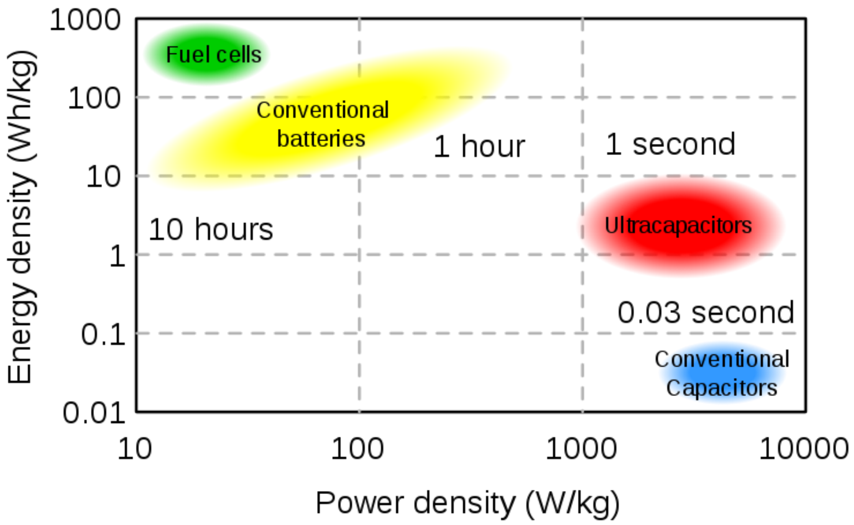

Figure 9. *Energy and power density and time scale of charge/discharge of different electricity storage technologies.*

3.1.3 Flywheel

A flywheel is a mechanical device with a significant moment of inertia used as a storage device for rotational energy. Recently, flywheels have become the subject of extensive research as power storage devices for uses in vehicles and power plants.

Compared with other ways of storing electricity, flywheel electricity storage systems have long lifetimes (lasting decades with little or no maintenance; full-cycle lifetimes quoted for flywheels range from in excess of 100,000 up to 10,000,000 cycles of use), high energy densities (100-130 Wh/kg) and large maximum power outputs. The energy efficiency (ratio of energy out per energy in) of flywheels can be as high as 90 %. Typical capacities range from 3 kWh to 133 kWh. Rapid charging of a system occurs in less than 15 minutes. The high energy densities often cited with flywheels can be a little misleading as commercial systems built have much lower energy density, for example 11 Wh/kg. (Investire 2003; Distributed Energy 2007)

Maximum energy density of flywheel energy storage is limited by material properties - density and maximum tension, as well as the form factor (the shape of the flywheel). Main advantage of flywheel energy storage is fast and easily adjustable power transfer. On the other hand, because of the high rotating speed, there are also pronounced risks at least in moving applications.

3.1.4 Compressed Air Storage

Compression of air generates a lot of heat and decompression requires heat. If no extra heat is added, the air will be much colder after decompression. If the heat generated during compression can be stored and used again during decompression, the efficiency of the storage improves considerably. This is aimed at in a German compressed air energy storage demonstration project ADELE, where a 1 GWh and 200 MW compressed air energy storage (CAES) is planned to be constructed after 2013 (RWE 2011).

The idea behind ADELE is to compress air at times of high electricity availability, to place the resulting heat in an interim heat-storage device and to inject the air into subterranean caverns. When electricity demand rises, this compressed air can be used to generate power in a turbine – while recovering the heat. This adiabatic process, in which the heat of the compressed air is not lost, but remains in the process for use in power generation, differs from existing compressed-air storage facilities, above all when it comes to the much higher round trip efficiencies (approx. 70 %). Also, the heating process no longer uses natural gas, which has been the case so far in the few utility-scale systems. These systems are actually gas turbine power plants with temporally separate compression and turbine stages, see the Iowa example below.

The Iowa Stored Energy Park (ISEP) will use electrical energy generated from a large wind farm located in Iowa. This wind power will be used to store compressed air in an underground geologic structure about 850 m underground. During peak power demands, the stored air will be returned to the surface, heated by natural gas in combustors and used to drive turbines that produce environmentally friendly and dispatchable electricity. In a conventional gas turbine power plant, the compressor stage consumes nearly two-thirds of the energy produced by the combustion and turbine stages. The use of the pre-compressed air thus reduces natural gas usage. The project will use two 134 MW generators and should be up by 2015. (ISEP 2011)

The first commercial CAES was a 290 MW unit built in Hundorf, Germany in 1978. The second commercial CAES was a 110 MW unit built in McIntosh, Alabama in 1991. The construction took 30 months and cost $65M (about $591/kW). This unit comes on line within 14 minutes. The largest ever commercial CAES is a 2,700 MW plant that is planned for construction in Norton, Ohio. This 9-unit plant will compress air to about 100 bar in an existing limestone mine some 670 m underground. (ESA 2011)

Smaller CAES systems have also been developed for vehicle propulsion, but commercial small-scale solutions have not yet emerged.

3.1.5 Pumped Hydro Storage

A pumped hydro power station mainly consists of two vertically separated water reservoirs. At the bottom reservoir, a turbine is placed that can be run both ways, or it could be a pump and turbine mounted on the same generator. The generator works as an engine during pumping.

When energy is stored, water is pumped up to the highest reservoir. The energy is harnessed by letting the water flow back through the turbine. The amount of energy that can be stored depends on the vertical distance between the reservoirs and the useful volume of the reservoirs. The power capacity depends on the size of the turbine.

Pumped hydro power stations are a mature, commercial technology with high efficiency. It is possible to recover more than 80 % of the energy that is put into the system. Pumped hydro is suitable for large scale energy storage and it is low cost technology. The main disadvantage is that it has specific site requirements: suitable, large reservoirs and big vertical distance between them.

3.1.6 Comparison of Electricity Storage Technologies

Large-scale stationary applications of electric energy storage can be divided in three major functional categories:

Power Quality. Stored energy, in these applications, is only applied for seconds or less, as needed, to assure continuity of quality power.

Bridging Power. Stored energy, in these applications, is used for seconds to minutes to assure continuity of service when switching from one source of energy generation to another.

Energy Management. Storage media, in these applications, is used to decouple the timing of generation and consumption of electric energy. A typical application is load leveling, which involves the charging of storage when energy cost is low and utilization as needed. This would also enable consumers to be grid-independent for many hours.

Although some storage technologies can function in all application ranges, most options would not be economical to be applied in all three functional categories. Figure 10 shows power and discharge time ratings of installed electricity storage systems. (ESA 2011)

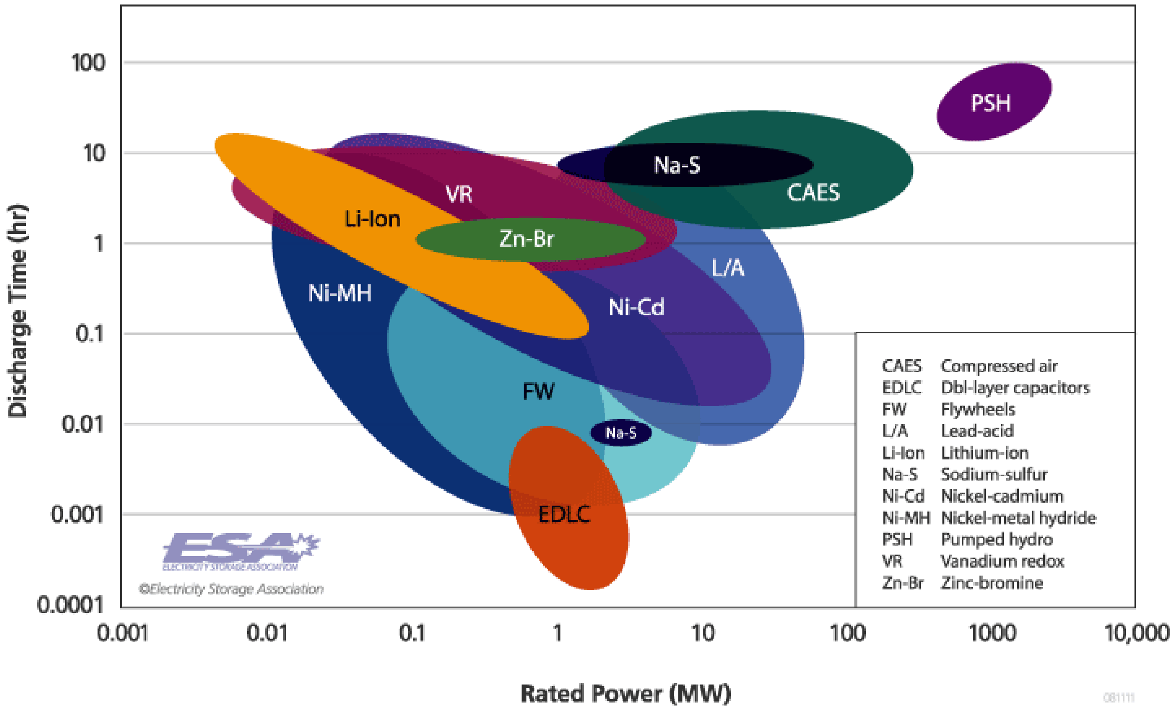

Figure 10. *System ratings of installed electricity storage systems. (ESA 2011)*

Different electricity storage technologies are compared qualitatively in Table 9. Volumetric and gravimetric energy density of storage technologies are mapped in Figure 11. The energy density ranges reflect the differences among manufacturers, product models and the impact of packaging. (ESA 2011)

Table 9. *Comparison of electricity storage technologies. (ESA 2011)*

Technology	Main advantages	Disadvantages	Power application (typically short discharge and recharge periods)	Energy application (longer discharge and recharge periods)
Li-ion	high power and energy densities, high efficiency	high production cost, requires special charging circuit	+	
Lead-Acid	low capital cost	limited cycle life when deeply discharged	+	
Ni-Cd	high power and energy densities, efficiency		+	(+)
NaS	high power and energy densities, high efficiency	production cost, safety concerns (addressed in design)	+	+
EC	long cycle life, high efficiency	low energy density	+	(+)
Flywheel	high power	low energy density	+	
CAES	high capacity, low cost	special site requirement, need gas fuel		+
Pumped hydro	high capacity, low cost	special site requirement		+

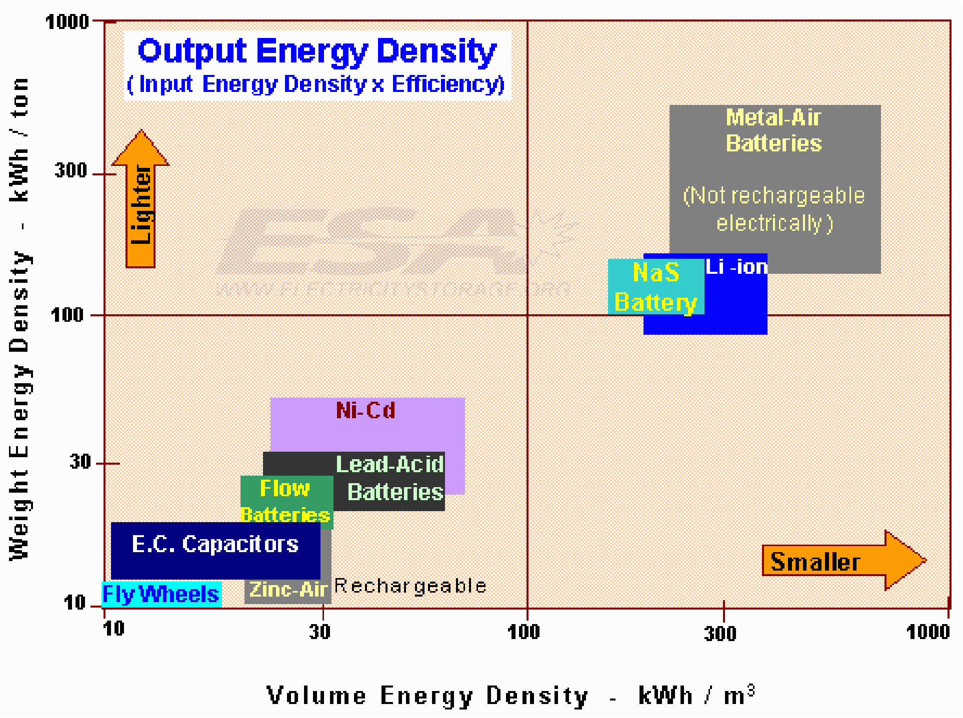

Figure 11. *Energy density of electricity storage technologies. (ESA 2011)*

Figure 12 shows the capital costs of electricity storage technologies. The costs of storage technologies are changing as they evolve. The cost ranges in this chart include approximate values in 2002 and the expected mature values in a few years, i.e. lower cost limits in the chart reflect the prices today. The Metal-Air batteries may appear to be the best choice based on their high energy density and low cost, but the rechargeable types have a very limited life cycle and are still under development. (ESA 2011)

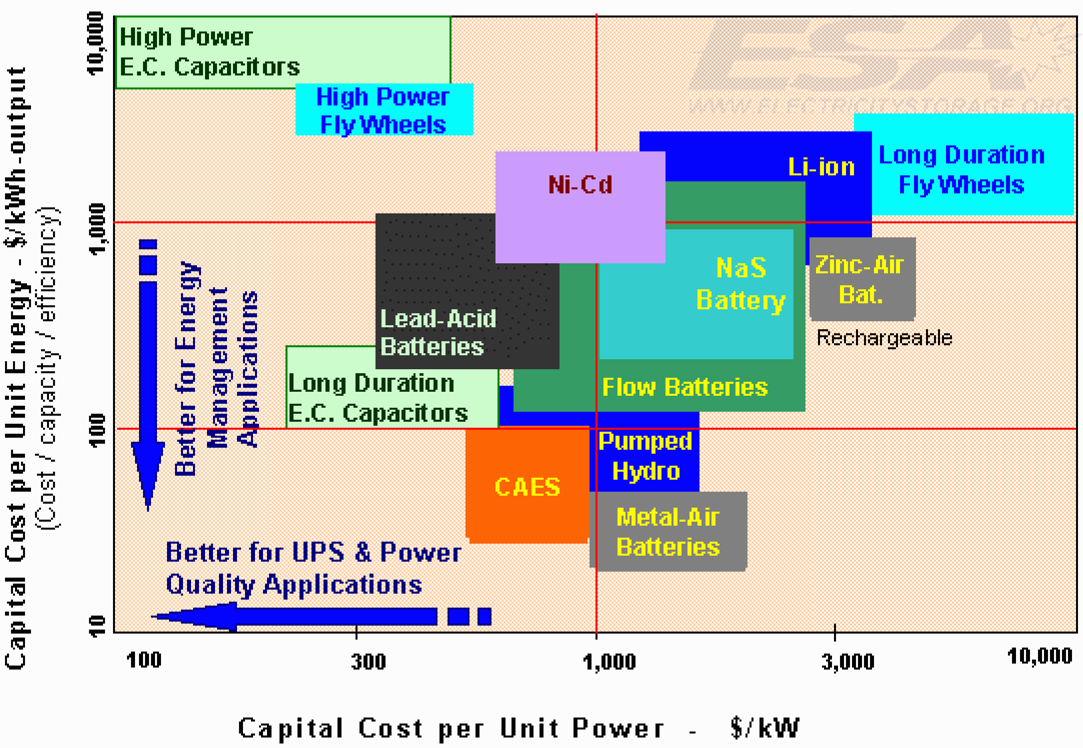

Figure 12. *Capital costs of electricity storage technologies. (ESA 2011)*

Figure 13 shows the lifetime and efficiency of electricity storage technologies. Efficiency and cycle life are two important parameters to consider along with other parameters before selecting a storage technology. Both of these parameters affect the overall storage cost. Low efficiency increases the effective energy cost as only a fraction of the stored energy could be utilized. Low cycle life also increases the total cost as the storage device needs to be replaced more often. The present values of these expenses need to be considered along with the capital cost and operating expenses to obtain a better picture of the total ownership cost for a storage technology. (ESA 2011)

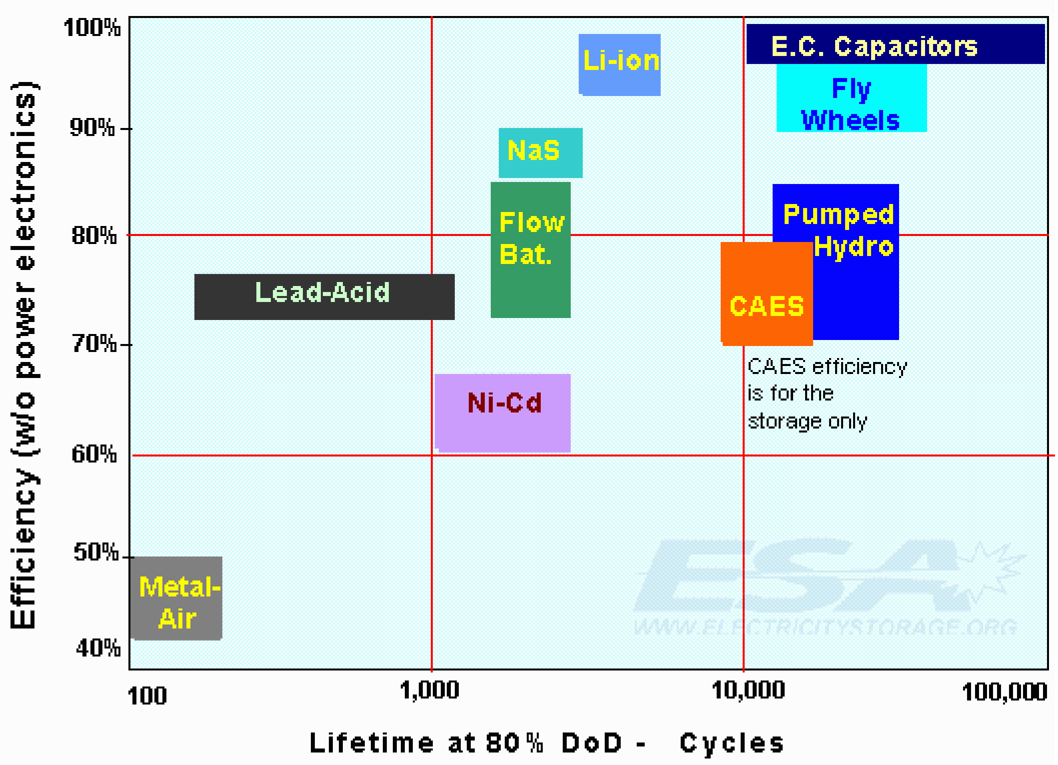

Figure 13. *Lifetime and efficiency of electricity storage technologies. DoD stands for depth of discharge. (ESA 2011)*

Finally, Figure 14 shows the capital cost per cycle for electricity storage technologies. Per-cycle cost can be the best way to evaluate the cost of storing energy in a frequent charge/discharge application, such as load leveling. This chart shows the capital component of this cost, taking into account the impact of cycle life and efficiency. For a more complete per-cycle cost, one needs also to consider O&M, disposal, replacement and other ownership expenses, which may not be known for emerging technologies. It should be noted that per-cycle cost is not an appropriate criterion for peak shaving or where the application is less frequent or the energy cost differential is large and volatile. (ESA 2011)

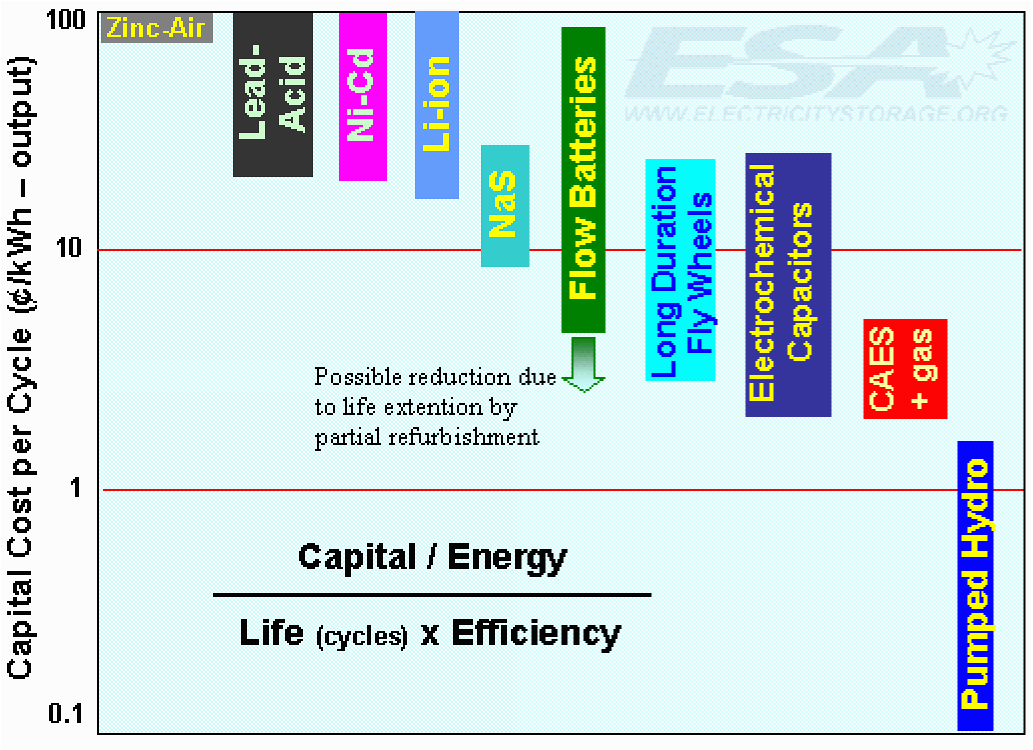

Figure 14. *Capital cost per cycle for electricity storage technologies; carrying charges, O&M and replacement costs are not included. (ESA 2011)*

3.2 Heat Storage

3.2.1 Sensible heat - Water Tanks

Increasing the temperature of liquid water in a container stores thermal energy as sensible heat. The main advantages of water-based sensible heat storage are that water is cheap, abundant and non-toxic, it has a relatively high specific thermal capacity, the store can be charged both thermally and with electricity, and the technology is simple and mature. The main disadvantages are that thermal losses increase as the temperature increases and that the temperature interval of liquid state is rather narrow which limits the storage capacity. In the case of small storage volumes, thermal insulation is the more important the longer storage times are needed. On the other hand, the larger the storage, the less significant the storage losses become: non-insulated underground seasonal storage from summer to winter can achieve 80 % storage efficiency if the storage volume is large enough (on the order of 10^5–10^6 m^3).

More common for utilities is to use a thermal buffer tank (in the size range of 10^3–10^4 m^3) which is charged during the weekdays and discharged during the weekends, thus allowing more or less constant operation of e.g. a district heating plant during the weekdays and shut-down at weekends. If used together with a CHP plant, sensible heat storage provides room for cost optimization on a daily basis: when the electricity price is high, the plant can be operated at full power even if thermal loads are lower than that; and when the electricity price is low, the plant can be shut-down or operated at minimum power while discharging thermal energy from the water tank.

3.2.2 Latent heat - Phase Change Materials

Phase change materials (PCMs) store large amounts of thermal energy when they melt (at their melting temperature), and release the same amount of energy when they freeze. The phase change happens almost at constant temperature which reduces thermal losses of the storage, compared to sensible heat storage. The melting temperature of many PCMs can be engineered to desired value.

There are three main groups of materials that are used or developed as PCMs: inorganic salt hydrates (M_nH_2O), organic paraffins (C_nH_{2n+2}) and fatty acids ($CH_3(CH_2)_{2n}COOH$) and eutectics (organic-organic, organic-inorganic, inorganic-inorganic compounds). Today there are also vegetable based PCMs on the market (Entropy Solutions Inc.).

Advantages and disadvantages of different PCMs depend on the type of PCM. Disadvantages include poor thermal conductivity in the solid state, relatively low volumetric thermal energy storage capacity, large volume change at phase change, and supercooling which results in lower temperature of discharging than that of charging. However, several commercial products and applications exist and more emerge all the time.

3.2.3 Passive Storage Solutions in Buildings

In buildings, passive thermal energy storage solutions are based on architecture, material selection and PCMs. Architecture offers many ways of taking advantage of solar energy and shading, thermal walls, as well as shielding from unwanted cooling due to wind. Massive construction offers thermal inertia (storage) and well-selected PCMs, which are usually integrated into construction materials, can offer thermal comfort during otherwise large daily temperature swings, especially in the spring and autumn.

4 Production Costs

Production cost is calculated per produced energy (€/kWh). In the case of CHP applications production costs are calculated both per produced electricity[10] and per overall energy production (electricity and heat). Production cost excludes the impacts of possible taxes and subsidies. Calculation has been carried out by using annuity method by dividing investment cost for the presumed lifetime with 5 % interest rate. For CHP applications the fuel cost is based on effective natural gas price, which is 5.3 c/kWh[11]. Annual operation for CHP applications is presumed to be 5,000 hours. In electricity production the annual operation hours vary between technologies; in production cost calculations the underlying operational hours are used.

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[10] When calculated per produced electricity, it is assumed that heat is not recovered, i.e. unit works as a condensing power plant.

[11] Porvoon Energia Oy. Natural gas price for 100 kW plant (incl. energy and transfer price, taxes, fixed charge etc.). Excluding VAT.

- PV: 1,000 hours per year (typical in southern Finland)
- Wind power: 1,800 hours per year (typical “close-to-coast” area)
- Hydro power: 4,000 hours per year

O&M cost includes operation, maintenance and insurance costs. In CHP applications the O&M costs are given per produced electricity, thus the heat recovery based maintenance can increase the overall O&M costs by few percent. Lifetime for CHP applications is presumed to be 15 years. For wind power the lifetime is 20 years, and for PV and hydro power the lifetime is 25 years. Electricity/heat production ratios in CHP applications vary from 0.2 to 1.0 depending on technology in question.

The economical characteristics of different energy production technologies have been given in Tables 1–8. The production costs are summarized in Table 10. First row represents production costs per produced electricity, and second row takes into account also heat production in CHP applications. Because of variation in e.g. lifetime, annual operation hours, production ratios, investment costs and fuel costs the given production costs are merely indicative.

Table 10. *Production costs of distributed energy production technologies.*

	CHP					Electricity		
	Microturbine	**Gas Engine**	**Stirling Engine**	**Fuel Cell***	**Steam Engine / Steam Turbine**	**PV**	**Small-scale Wind Power**	**Micro-scale Hydro Power**
Electricity production cost (c/kWh$_e$)	19.0–38.0	17.5–23.0	21.0–43.5	12.5–24.0	18.0–42.0	21.0–36.0	12.0–32.0	8.0–14.0
Energy production cost (c/kWh)	7.5–11.5	9.0–12.0	9.5–15.5	8.0–14.0	9.0–14.5	-	-	-

*) Target price for commercial products.

5 Suitable Technologies for Skaftkärr Area

5.1 Selection of Technologies

This study examines two different applications of distributed energy production: 1) *single-family house* and 2) *house group*. Single family house has 140 square meters. House group consists of ten single-family houses. Energy demand of these buildings is based on *National Building Code of*

Finland[12] that becomes effective in 2012. Assumptions made in energy demand of residential applications are as follows:

- Single-family house: electricity 7,700 kWh, heat (incl. hot water) 10,500 kWh
- House group: electricity 77,000 kWh, heat (incl. hot water) 105,000 kWh

The assumptions behind the above mentioned energy demands are that electricity consumption is 55 kWh/m^2 and heat is produced using 20 % renewable and 80 % fossil energy sources. Thus heat demand is 75 kWh/m^2. More information on energy efficiency requirements of new buildings can be found from Ministry of the Environment web-page by searching *regulations and guidelines of energy management in buildings*.

The required power output of a certain technology depends on its annual operation hours (operational availability). For example gas engines can operate all year round (excl. maintenance break) but photovoltaics can generate electricity only when enough solar radiation is available, i.e. approximately 1,000 hours.

In Skaftkärr, there are some boundary conditions for different technologies, e.g., there is no hydropower available and the area is not especially suitable for small-scale wind power production. Furthermore, the size of the systems considered causes some limitations for CHP technology. Taking these boundary conditions into account, Table 11 represents the suitable applications for distributed energy production technologies for Skaftkärr.

Table 11. *Suitable applications for distributed energy production technologies.*

	Single family house	House group (8-10 households)	Residential area* (over 10 households)
CHP			
Microturbine		(+)	+
Gas Engine		+	+
Stirling Engine	(+)	+	+
Fuel Cell	(+)	+	+
Steam Engine / Steam Turbine			(+)
ORC			(+)

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[12] Ministry of the Environment. D3 Energy management in buildings - Regulations and guidelines 2012. http://www.ymparisto.fi/default.asp?node=15617&lan=fi (Finnish).

Electricity			
Photovoltaics	+	+	+
Small-scale Wind Power		(+)	+
Micro-scale Hydro Power		(+)	+

*) Not included in the study.

The technologies considered in hereinafter cases are photovoltaics, gas engine and batteries (Li-ion in electric vehicles and lead-acid in stationary system). Microturbines, steam engines, steam turbines and ORC are not viable or cost-effective technologies for the size range of this study. Stirling engine and fuel cell are not yet commercially mature or reliable technologies to be used as primary energy production method.

5.2 Case 1: Single-family house

5.2.1 Assumptions and sizing of the system

In the case of single-family house photovoltaics is used in power production. The PV system is sized to cover half of annual electricity demand of the building (3,850 kWh). Thus the power output is 3.5 kW_p. This can be acquired with roughly 40 square meter panel area, with assumption that one square meter produces approximately 100 kWh electricity annually[13].

The calculations are carried out using two different options of implementation. In both options household has electric vehicle with Li-ion battery capacity of 24 kWh. The battery is assumed to be charged 50 times per year by DoD of 80 %. The base load of the house is 200 W[14] and hot water boiler has volume of 300 litres. PV system is used to cover a part of the annual electricity demand of these applications.

In **option 1** the surplus electricity is fed to the grid. Based on a rough energy balance model of production and consumption, on a typical sunny day the order of priority in using solar electricity for housing applications is as follows:

1. Base load (11 %)
2. Electric vehicle (12 %)
3. Hot water boiler (17 %)
4. Feed to the grid (60 %)

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[13] In calculations the annual operation is 1,095 hours.

[14] Base load remains constant year-round. Refrigerator-freezer uses 40 W, ventilation and pumps use 100 W, devices' standby power uses 30 W and 30 W can be allocated to other undefined applications.

When it is cloudy and less solar radiation available the household needs to purchase electricity from the electricity vendor.

In **option 2** the electricity that is not used in base load, EV and boiler, can be used to charge a stationary lead-acid battery instead of feeding it to the grid. If the additional battery is present, its capacity is sized according to typical cloudless day of 6 hour solar radiation. Thus, the produced electricity, that is not used to cover the base load of the house, electric vehicle charging and hot water boiler, is fed to the stationary battery. In this case, the capacity of stationary battery is 12.6 kWh. A lead-acid battery with this capacity level can weight about 350–370 kilograms, and required space is about 0.2 cubic meters. Battery lifetime is between 10 and 20 years, depending on number of charging cycles done per year as well as depth of discharge.

5.2.2 Cost and Profitability Analysis

Investment costs of the two system options are presented in Table 12. Labor costs (incl. all materials needed for installations) are estimated to be equal to the costs of PV and inverter. Lead-acid battery costs 150 €/kWh$_{capacity}$. Costs related to electric vehicle and hot water boiler are excluded, because existence of these applications is not dependent on selection of energy system. The alleged lifetime of PV module is 25 years. Lifetime of inverter and lead-acid battery is assumed to be 15 years.

Table 12. *Investment costs for two different options in the case of a single-family house.*

	Option 1	Option 2	
PV module	5,274	5,274	€
Inverter	1,406	1,406	€
Labor*	6,680	6,680	€
Stationary battery (lead-acid)	-	1,886	€
Total	**13,661**	**15,247**	**€**

*) Includes all balance of system (BOS) costs except inverter.

Operation and maintenance cost for PV system averages 0.3 cents per kWh electricity produced. Inverter and possible lead-acid battery (in option 2) are assumed to be replaced after 15 years of operation.

All the electricity purchase avoided via PV produced energy generates profit to the household. Electricity price used in calculations is 15.9 c/kWh[15], including energy and transfer costs as well as all taxes. The price for electricity that is fed to the grid in option 1 is assumed to be 4.0 c/kWh. Electricity prices are to remain constant during the whole period. Thus, when the system is downscaled, more electricity is used directly which makes system more cost-effective compared to situation where the produced electricity is fed into the grid. The more accurate initial data used in calculations is given in Appendix 1.

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[15] Average in Southern Finland with annual electricity demand of 5,000 kWh.

Table 13 shows the interest-free payback periods of the two investment options. Subsidies are also taken into account in calculations[16]. When using 25-year interest-free investment period the net present value (NPV) for option 1 is **-2,000 euros** (negative) and for option 2 **-3,500 euros** (negative). Internal rate of return (IRR) for both options is negative as well. When taken subsidies into account the NPVs are **2,800 euros** and **1,200 euros**, respectively. Thus, subsidies turn IRR slightly positive in both options, i.e. **2.4 %** and **0.9 %**, respectively.

Table 13. *Key figures for two different options in the case of a single-family house.*

	Option 1	Option 2	
Unsibsidized			
Payback period, i = 0 %	> 30	> 30	years
Subsidized			
Payback period, i = 0 %	20	23	years

As the labor cost for PV system is a major part of the investment, there is need to perform a sensitivity analysis of its effects on overall profitability. If the labor cost can be halved and subsidies are present, the NPV for options 1 and 2 are 4,400 euros and 2,900 euros, respectively, corresponding to payback periods of 14 and 15 years, respectively. Figure 15 illustrates annual (bars) and cumulative (line) cash flow of the single-family house investment case in different calculation cases. It highlights the impact of subsidies and labor costs to investment's interest-free payback period in option 1. Figure 16 does the same for option 2.

Electricity price contributes directly to investment profitability as well. The real price of electricity in Finland has increased rapidly in short term and the trend can be presumed to continue in future. If the annual increase in electricity price is 3.5 %[17] and subsidies are taken into account, the interest-free payback period for option 1 and 2 drops to 14 years, even with the original labor costs (see Table 12).

---

[16] The city of Porvoo subsidizes investments that focus on renewable energy implementation. The maximum subsidy level for households is 20 % (covering equipment costs). Government gives also tax concession (covering labor costs) to households that perform property restorations. More information on subsidies can be found from web-pages of Porvoo and Finnish Tax Administration.

[17] Average increase in real price of electricity in the past decade in Finland. See e.g. www.sahkonhinta.fi (Finnish).

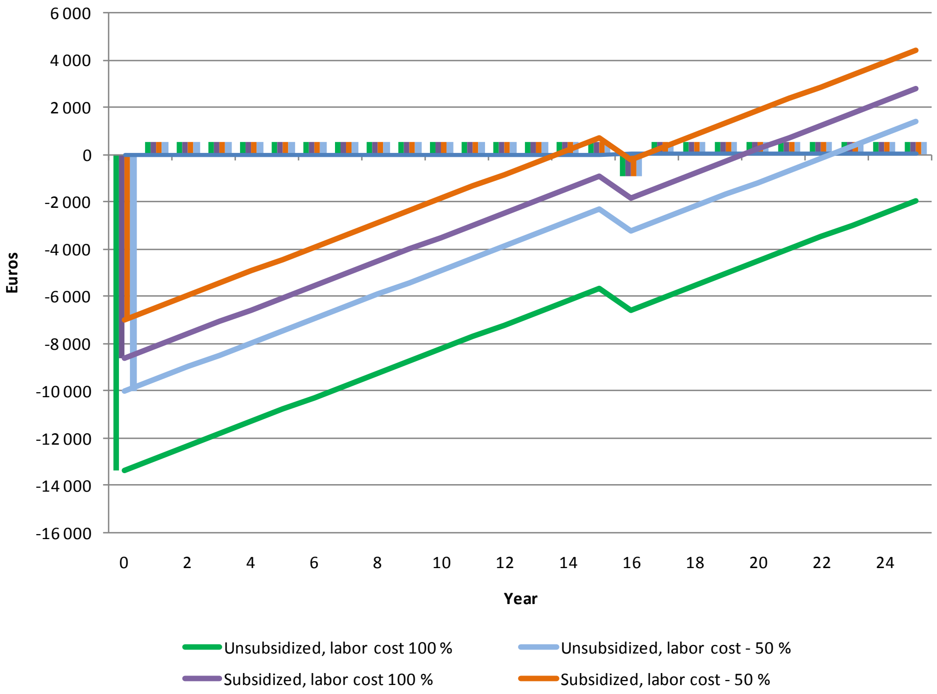

Figure 15. *Sensitivity analysis on profitability of the single-family house investment without stationary battery (option 1).*

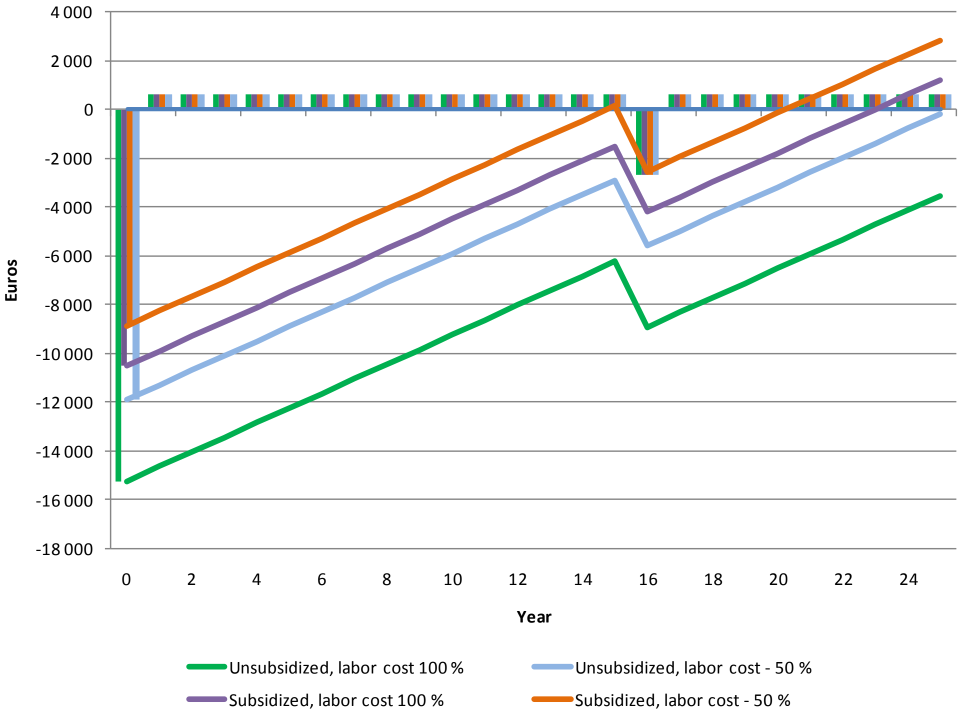

Figure 16. *Sensitivity analysis on profitability of the single-family house investment with stationary battery (option 2).*

5.3 Case 2: House Group

5.3.1 Assumptions and sizing of the system

In the case of house group photovoltaics and gas engine are used in energy production. Gas boiler is also used to produce heat during the peak season. In **option 1** the PV system is sized to cover 20 % of annual electricity demand of the buildings (15,400 kWh). Thus the power output is 14.1 kW_p. This can be acquired with roughly 155 square meter panel area, with assumption that one square meter produces approximately 100 kWh electricity annually[18]. In **option 2** the PV system is excluded.

Gas engine has an output of 5.5 kW_e and 12.5 kW_{th}. Total energy efficiency in CHP production is approximately 88 % and annual operation 5,500 hours on average. Thus, annual fuel consumption is more than 110 MWh. Gas engine is assumed to use natural gas as a fuel; other alternative is biogas but this is not considered in this study[19]. Gas boiler is used for additional heat production when outside temperature is abundantly below zero degrees and heat demand is high. Gas boiler has a thermal output of 50 kW and is used as a centralized hot water boiler of the house group. Boiler efficiency is assumed to be 90 % and its annual operation time is 720 hours, which is based on rough spreadsheet calculation model. Thus, annual natural gas consumption is roughly 40 MWh. Annual energy production of gas engine and gas boiler is:

- *Gas engine:* 30,300 kWh_e and 69,000 kWh_{th}
- *Gas boiler:* 36,000 kWh_{th}

Every household is assumed to have electric vehicle with Li-ion battery capacity of 24 kWh. The battery is charged 50 times per year by DoD of 80 %. The base load of the house group is 2,000 W[20]. Alternative energy system is used to cover a part of the annual electricity demand of electric vehicles and base load. Half of the surplus electricity, that is not used to cover the base load of the house and electric vehicle charging, is fed to the grid and other half is used to charge a stationary lead-acid battery.

In **option 1** (PV/gas engine system) the stationary battery capacity is sized according to typical cloudless day of 6 hour solar radiation. In **option 1**, the capacity of stationary battery is 71 kWh. A lead-acid battery with this capacity level can weight about 2,000 kilograms, and required space is about one cubic meter. In **option 2**, the battery capacity demand drops to 29 kWh (800 kg/0.4 m^3) as PV is excluded. Battery lifetime is between 5 and 10 years, depending on number of charging cycles done per year as well as depth of discharge. Lifetime is shorter compared to single-family house case because charging cycles increase in larger-scale applications.

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[18] In calculations the annual operation is 1,095 hours.

[19] Utilizing biogas requires investments on gasification equipment and in addition O&M costs rise. These costs are compensated via government renewable energy subsidies but due to simplicity this alternative is left outside the scope of this study.

[20] Base load remains constant year-round. In one house the refrigerator-freezer uses 40 W, ventilation and pumps use 100 W, devices' standby power uses 30 W and 30 W can be allocated to other undefined applications.

Gas engine and gas boiler as well as stationary battery should be centralized in one location. Energy production equipment warm up this *service building*, which is important for stationary battery unit that rapidly loses its capacity when temperature drops below zero. Solar panels are assumed to be centralized as well, e.g. into service building structures. When planning PV installation the right adjustments and angle of the panels need to be emphasized in order to assure a maximum electricity yield and gravitational drain of snow from the panel surface; this stands for single-house installations as well.

5.3.2 Cost and Profitability Analysis

Investment costs of the two system options are presented in Table 14. Labor costs (incl. all materials needed for installations) are estimated to be equal to the costs of PV and inverter. Lead-acid battery costs 150 €/$\text{kWh}_{\text{capacity}}$ and gas boiler 100 €/kW (investment cost, including labor). Costs related to electric vehicles, service building and construction of heating network are excluded. The alleged lifetimes of relevant equipment are:

- PV module: 25 years
- PV inverter: 15 years
- Gas engine: 15 years
- Gas boiler: 20 years
- Lead-acid battery: 5–10 years

Table 14. *Investment costs for two different options in the case of house group.*

	Option 1	Option 2	
PV			
Module	21,096	-	€
Inverter	5,626	-	€
Labor*	26,721	-	€
Gas engine			
Equipment + labor	18,000	18,000	€
Gas boiler			
Equipment + labor	5,000	5,000	€
Stationary battery (lead-acid)			
Battery unit	10,656	4,327	€
Total	**87,099**	**27,327**	**€**

*) Includes all balance of system (BOS) costs except inverter.

Operation and maintenance cost for PV system averages 0.3 cents per produced kWh_e and for gas engine 2.0 cents per produced kWh_e. O&M cost for gas boiler is assumed to be 0.2 cents per produced kWh_{th}. Possible PV inverter (in option 1) is assumed to be replaced after 15 years. Replacement interval for stationary lead-acid battery is assumed to be 5 years.

Assumptions concerning electricity prices are equal to the case of single-family house. Natural gas costs 5.3 c/kWh[21]. In calculations the heating method of comparison is district heating. Alternative heat production replaces district heat purchase, in which case avoided cost per produced kWh_{th} is 7.4 cents[22]. Energy prices are to remain constant during the whole period. The more accurate initial data used in calculations is given in Appendix 2.

Table 15 shows the interest-free payback periods of the two investment options. Subsidies are also taken into account in calculations[23]. When using 15-year interest-free investment period the net present value (NPV) for option 1 is **-32,000 euros** (negative) and for option 2 **12,500 euros**. Internal rate of return (IRR) for option 1 is negative and for option 2 **5.3 %**. When taken subsidies (for PV equipment only) into account the NPV in option 1 is **-26,500 euros** (negative). NPV in option 2 remains the same as unsubsidized because energy system does not implement renewable energy. Thus, IRR for option 1 remains negative and like NPV, also IRR remains constant in option 2.

Table 15. *Key figures for two different options in the case of house group.*

	Option 1	Option 2	
Unsibsidized			
Payback period, i = 0 %	> 30	10	years
Subsidized			
Payback period, i = 0 %	29	10	years

As the labor cost for PV system is a major part of the investment, there is need to perform a sensitivity analysis of its effects on overall profitability. If the labor cost can be halved and subsidies are present, the NPV for options 1 is -13,200 euros (negative), corresponding to payback periods of 27 years. Subsidies are not available in option 2 since PV system is not installed. Hence, labor costs of PV installation are also excluded, and this makes sensitivity analysis vain in option 2. Figure 17 illustrates annual (bars) and cumulative (line) cash flow of the house group investment case in different calculation cases. It highlights the impact of subsidies and labor costs to investment's interest-free payback period in option 1. Figure 18 illustrates cash flows in option 2.

Electricity and district heat prices contribute directly to investment profitability. If the annual increase in both electricity and heat price is 3.5 %, natural gas price remains constant and investment subsidies are taken into account, the interest-free payback period for option 1 is 13 years, even with the original labor costs (see Table 14). Payback period for option 2 drops to 7 years when price development is taken into account.

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[21] Porvoon Energia Oy. Natural gas price for 100 kW plant (incl. energy and transfer price, taxes, fixed charge etc.). Excluding VAT.

[22] Porvoon Energia Oy. District heat price for single-family house customer, 3.3.2011.

[23] The city of Porvoo subsidizes investments that focus on renewable energy implementation (available only in option 1). The maximum subsidy level is 20 % (covering equipment costs). Government gives also tax concession (covering labor costs) to households that perform property restorations (not available for co-op applications). More information on subsidies can be found from web-pages of Porvoo, Finnish Tax Administration and Ministry of Employment and the Economy.

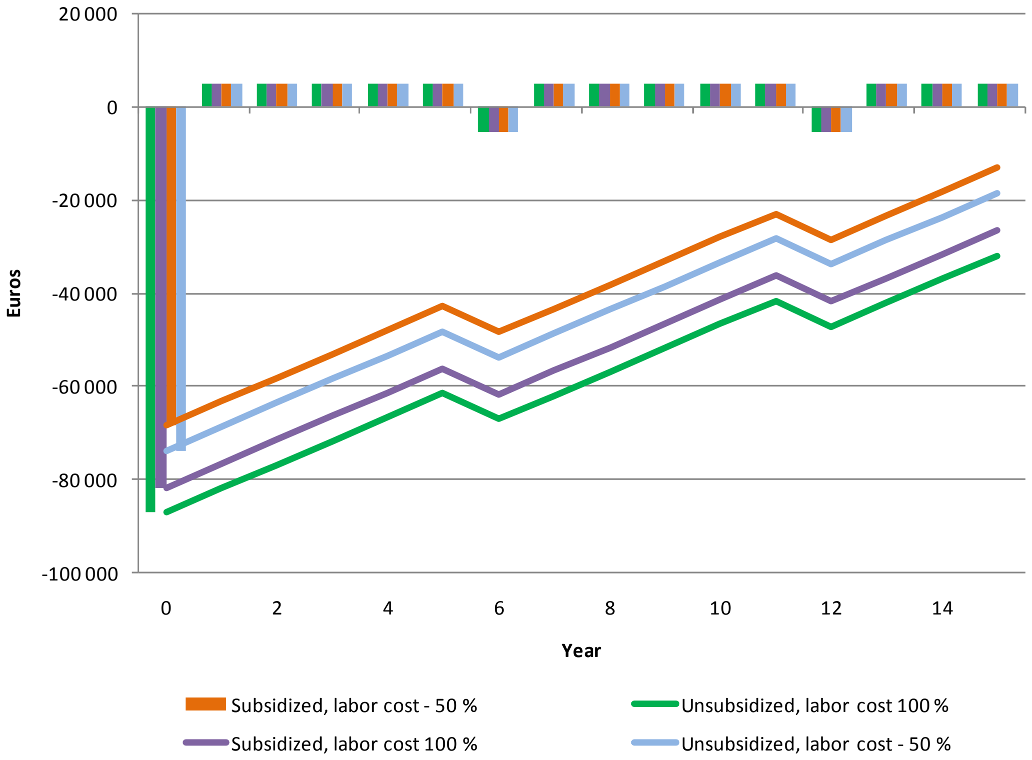

Figure 17. *Sensitivity analysis on profitability of the house group investment with PV system (option 1).*

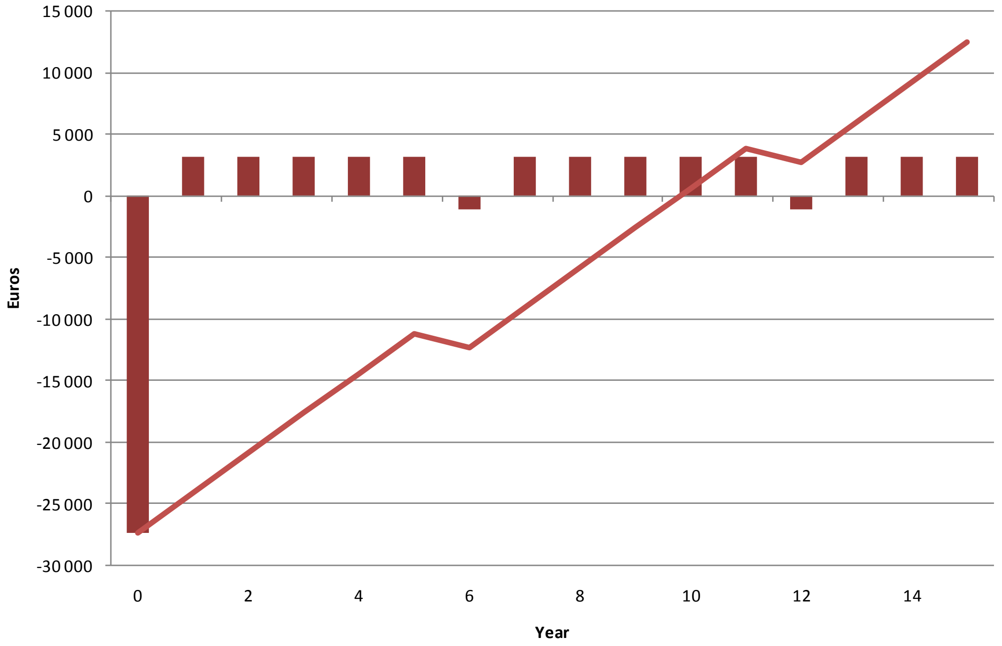

Figure 18. *Annual and cumulative cash flows of the house group investment without PV system (option 2).*

6 Identified Actors in Value Chain

This chapter introduces actors in value chains of distributed energy production and energy storage. Identified manufacturers and suppliers of energy production technologies are selected and listed in Table 16 based on domestic aspects, i.e. the listed actors have domestic representation and all the equipment as well as related maintenance services are available in Finland. Microturbines, gas engines, fuel cells and photovoltaics are the most suitable technologies when considering both cost-efficiency and local characteristics of Skaftkärr area. Steam engines, steam turbines and ORC are not included in the table since these technologies are not in practice suitable for the size range in this study. Wind and hydropower are included in the list even though they are not relevant in the case of Skaftkärr. However, they may be relevant in other part of Porvoo or Southern Finland.

Table 16. *Identified domestic actors in value chain of distributed energy production.*

	Manufacturer	Supplier / Importer	Service / Parts	Contact info / web page	Other
Microturbine					
Sarlin Oy		X	X	www.sarlin.com	Turbine units have electrical power output of 30, 65 and 200 kW. Larger applications possible via parallel circuit.
Konwell Oy		X	X	www.konwell.fi	Cooperation with Czech company G-Team.
NHK-Keskus		X	X	www.nhk.fi	Power output 30 kWe / 60 kWth. Larger applications possible via parallel circuit. Designed for biogas applications.
Ekogen Oy		X	?	www.ekogen.fi	Power output 100 kWe / 300 kWth.
Gas Engine					
GASEK Oy	(X)	X	X	www.gasek.fi	Power output 20-50 kWe / 60-100 kWth. Including wood gasifier.
Entimos Oy	(X)	X	?	www.entimos.fi	Suitable fuel power range 1-7 MWfuel. Including gasifier (biomass and REF).
Fortel Components Oy		X	?	www.fortel.fi/components	Supplier of gasification-based CHP application in Kempele (35 kWe).
Höyrytys Oy		X	X	www.hoyrytys.fi	Power output ≥ 30 kW.

Stirling Engine					
Ekogen Oy		X	?	www.ekogen.fi	Power output 9 kWe/50 kWth. Technology in pilot stage.
eGen Oy	?	?	?	http://egen.fi	Technology under development.
Fuel Cell					
Wärtsilä Oyj	X	X	X	www.wartsila.com	Pilot-scale SOFC application in Vaasa has been successful (20 kWe/15 kWth). Cooperation with Danish company Topsoe Fuel Cell.
Oy Hydrocell Ltd.	X	X	X	www.hydrocell.fi	Low-temperature fuel cells with power output of 1-1,000 kW.
Photovoltaics					
NAPS Systems Oy	X	X	X	www.napssystems.com	PV systems for wide size range.
OPAM	X	X	X	www.opamgcee.com	PV systems for wide size range.
Finnwind Oy		X	X	www.finnwind.fi	PV systems for up to 20 kW. Panel manufacturer Solarwatt.
Frisnet Oy		X	X	www.frisnet.fi	PV systems for wide size range. Panel manufacturer IBC SOLAR AG.
JN-Solar		X	X	www.jn-solar.fi	PV systems for residential applications. Uses various panel manufacturers.
Wind Power					
Eagle Tuulivoima Oy	X	X	X	www.eagle.fi	Wind power systems for up to 20 kW.
Finnwind Oy	X	X	X	www.finnwind.fi	Wind power systems for up to 5.3 kW.
Posira Oy	X	X	X	http://posira.fi	Small-scale wind power for residential applications. Company owned by St1.
Hydro Power					
Oy M&S Power Ltd.	?	?	?	www.m-et-s-power.net	Planning and construction of micro-scale hydro power plants.
Saahkarin Kone Ky	X	X	?	www.pienvesivoima.fi	Typical power output 20-200 kW.

Various energy storage technologies are introduced in this study. Listing of manufacturers and suppliers of these technologies is not advantageous because in practice only batteries are viable for the considered applications. Supercapacitors, flywheels and compressed air storages are either too expensive or not in the right size range for residential electricity storage applications. In addition, local characteristics create barrier to pumped hydro storage.

European Batteries develops advanced lithium-ion battery solutions. The modules consist of lithium-iron phosphate cells and advanced battery management systems. Modules can be installed in containers with necessary protection and cooling equipment. They can operate as reserve power systems or stationary energy storages. The size range of the systems is from 1 kWh up to several MWh. (EB 2011) Other domestic suppliers are e.g. *Akkuvoima Oy*, which supplies batteries manufactured by e.g. *NorthStar Battery*, *Hoppecke Batterien*, *Trojan*, *Duracell Professional*, *Sanyo*, *Renata*, *CT-Leader* and *Power-One*. Akkuvoima’s product range comprises various battery technologies, including lead-acid, nickel-cadmium and lithium-ion batteries in multi-kW class. (Akkuvoima 2011)

Electric vehicles are supplied by almost all car manufacturers. The most common battery type used is lithium-ion with capacity range of 20 to 30 kWh.

7 Summary and Conclusions

This study introduced available distributed energy production technologies and various alternative technologies to store energy. Technical and economical characteristics of small-scale CHP and electricity production technologies were presented. The main object was to show that there are technically viable technologies to produce and store energy in small power range. However, local geographical and climate characteristics, buildings' energy demand and various preferences determine which technologies are economically viable for application in question.

Technical and economical suitability of different technologies were demonstrated through two cases. First case considered a single-family house with photovoltaics system and complementary battery unit. Second case included CHP production with centralized stationary battery unit in house group application; photovoltaics were examined as an optional system. Cases showed that cost-effectiveness of energy systems, especially in the smallest-scale applications, is hard to achieve without subsides. Distributed energy systems become more attractive when up-scaled to extent of house group. In general, public sector subsidies and labor-intensive installation costs are also noteworthy factors when considering profitability of the investment. Especially labor cost of photovoltaics installations is very crucial factor. If installation costs can be decreased by smart building integration, this may lead to remarkable better cost efficiency, especially in the small-scale solutions.

There are several domestic actors in the value chains of energy production and energy storage technologies. This is important aspect when considering a comprehensive energy system delivery as well as available customer service. Distributed energy production can enhance local self-sufficiency and business activities, as well as reduce greenhouse gas emissions. Solutions of distributed energy systems are developing and to become practical alternatives within residential applications. Distributed energy production is a vital part of future smart grid concept and it is important that municipalities take this into account when planning new residential areas and related energy options.

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Appendix 1. Initial data for single-family house case

PV		
Roof area	39	m2
Yield	100	kWh/m2
Electricity demand	7 700	kWh
Demand covering	50 %	
Electricity production	3 850	kWh
Operation	1 095	hours
Size/power	3,5	kWp

Battery - EV		
Capacity	24,0	kWh
Charging starts from	20 %	
Charging cycles per year	50	

Boiler		
Volume	300	litres
Temperature difference	20	K
Days per year	365	days
Availability	50 %	
Electricity	1 274	kWh

Base load		
Power	200	W
Hours	8 760	hours
Availability	50 %	
Electricity	876	kWh

Stationary battery (Lead-acid)		
Energy density (per weight)	0,035	kWh/kg
Weight	359	kg
Energy density (per volume)	70	kWh/m3
Volume	0,18	m3
Capacity	12,6	kWh
Price per output	150	e/kWh
Charging cycles per year	74	
Charging starts from	20 %	
Cycle lifetime	1 000	cycles

Year		
PV		
Hours	1 095	hours
Production	3 850	kWh
Base load	876	kWh
EV	960	kWh
Boiler	1 274	kWh
Feed/battery	740	kWh

Appendix 2. Initial data for house group case

PV	Single	Group	
Roof area	39	154	m2
Yield	100	100	kWh/m2
Electricity demand	7 700	77 000	kWh
Demand covering	50 %	20 %	
Electricity production	3 850	15 400	kWh
Operation	1 095	1 095	hours
Size/power	3,5	14,1	kWp

Battery - EV	Single	Group	
Capacity	24,0	240	kWh
Charging starts from	20 %	20 %	
Charging cycles per year	50	50	

Base load	Single	Group	
Power	200	2 000	W
Hours	8 760	8 760	hours
Availability	50 %	50 %	
Electricity	876	8 760	kWh

Stationary battery (Lead-acid)		Group	
Energy density (per weight)		0,035	kWh/kg
Weight		2 030	kg
Energy density (per volume)		70	kWh/m3
Volume		1,01	m3
Capacity		71,0	kWh
Price per output		150	e/kWh
Charging cycles per year		164	
Charging starts from		20 %	
Cycle lifetime		1 000	cycles

Gas engine		Group	
Electrical output		5,5	kW
Thermal output		12,5	kW
CHP efficiency		88 %	
Fuel input		20,6	kW
Annual operation		5 515	hours
Electricity production		30 333	kWh
Heat production		68 938	kWh
Fuel consumption		113 451	kWh

Gas boiler		Group	
Sized for maximum demand		50,0	kW
Temperature difference		50	K
Fuel input		55,6	kW
Efficiency		90 %	
Annual heat production		36 063	kWh
Annual operation		721	hours
Fuel consumption		40 069	kWh
Cost		100	e/kW

PV	Single	Group	
Roof area	39	0	m2
Yield	100	100	kWh/m2
Electricity demand	7 700	77 000	kWh
Demand covering	50 %	0 %	
Electricity production	3 850	0	kWh
Operation	1 095	1 095	hours
Size/power	3,5	0,0	kWp

Battery - EV	Single	Group	
Capacity	24,0	240	kWh
Charging starts from	20 %	20 %	
Charging cycles per year	50	50	

Base load	Single	Group	
Power	200	2 000	W
Hours	8 760	8 760	hours
Availability	50 %	50 %	
Electricity	876	8 760	kWh

Stationary battery (Lead-acid)		Group	
Energy density (per weight)		0,035	kWh/kg
Weight		824	kg
Energy density (per volume)		70	kWh/m3
Volume		0,41	m3
Capacity		28,8	kWh
Price per output		150	e/kWh
Charging cycles per year		210	
Charging starts from		20 %	
Cycle lifetime		1 000	cycles

Gas engine		Group	
Electrical output		5,5	kW
Thermal output		12,5	kW
CHP efficiency		88 %	
Fuel input		20,6	kW
Annual operation		5 515	hours
Electricity production		30 333	kWh
Heat production		68 938	kWh
Fuel consumption		113 451	kWh

Gas boiler		Group	
Sized for maximum demand		50,0	kW
Temperature difference		50	K
Fuel input		55,6	kW
Efficiency		90 %	
Annual heat production		36 063	kWh
Annual operation		721	hours
Fuel consumption		40 069	kWh
Cost		100	e/kW

Year (option 1)		
PV		
Hours	1 095	hours
Electricity production	15 400	kWh
Base load (electricity)	8 760	kWh
EV	0	kWh
Stationary battery	3 320	kWh
Feed (grid)	3 320	
Gas engine		
Hours	5 515	hours
Electricity production	30 333	kWh
Heat production	68 938	kWh
Base load (electricity)	8 760	kWh
EV	9 600	kWh
Stationary battery	5 986	kWh
Feed (grid)	5 986	
Gas boiler		
Hours	721	hours
Heat production	36 063	kWh
Total electricity production	45 733	kWh
Total heat production	105 000	kWh
Total battery charging/discharging	9 306	kWh
Total feed to the grid	9 306	kWh

Year (option 2)		
PV		
Hours	1 095	hours
Electricity production	0	kWh
Base load (electricity)	0	kWh
EV	0	kWh
Stationary battery	0	kWh
Feed (grid)	0	
Gas engine		
Hours	5 515	hours
Electricity production	30 333	kWh
Heat production	68 938	kWh
Base load (electricity)	11 030	kWh
EV	9 600	kWh
Stationary battery	4 851	kWh
Feed (grid)	4 851	
Gas boiler		
Hours	721	hours
Heat production	36 063	kWh
Total electricity production	30 333	kWh
Total heat production	105 000	kWh
Total battery charging/discharging	4 851	kWh
Total feed to the grid	4 851	kWh