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Chapter 8

Integration of Renewable Energy into Present and Future Energy Systems

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Chapter 8 has been allocated a total of 102 pages in the SRREN. The actual chapter length (excluding references & cover page) is 110 pages: a total of 8 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

Chapter 8: Integration of Renewable Energy into Present and Future Energy Systems

Executive Summary

Integration of large shares of renewable energy (RE) into the energy supply system (presently dominated by fossil fuels) will require a major paradigm shift rather than just making simple, minor adjustments. Due to the variable nature of most RE sources, either over seasons or within minutes, cost-effective integration into present heating/cooling networks, natural gas grids, liquid transport fuel supply and distribution, buildings, industrial processes, and in particular into electricity supply systems, has proven to be challenging. Many examples exist of successful integration of specific RE technologies, often as a result of supporting local and national policies and measures that depend on the RE cost-effectiveness, social acceptance, reliability and co-benefits including energy security. However, if greater shares of RE are to be accommodated, other energy markets may need adapting and expanding and to avoid continued growth of GHG emissions from fossil fuel combustion, the rate of RE penetration will need to be more rapid than has been the case to date.

In the long-term, RE has the technical potential to provide the major share of global energy. Indeed some regions and towns are already close to achieving 100% RE supply, including for heat and local transport. Through measured system integration, there are few, if any, technical limits to the level of RE penetration in the many parts of the world where sufficient resources exist. RE could provide the full range of desirable energy services to both large and small communities in both developed and developing countries. The necessary transition will require considerable investment in new infrastructure, (including novel transport methods, distributed energy systems, energy storage, electricity transmission on- and off-shore, intelligent grids) together with improvements in energy efficiency for both the supply-side and final end-use.

Increased deployment of RE in both urban and rural areas will depend upon local and regional resources, energy demand patterns, project finance, and current markets. Limitations to deployment exist where specific site conditions, local RE resource characteristics and energy demand profiles are not conducive. The general and specific requirements to overcome barriers preventing greater penetration of RE into heating, cooling, electricity, gas and liquid networks, autonomous buildings and communities, are reasonably well understood. Several real-world case studies have been included in the chapter to outline the benefits of RE and to illustrate how integration approaches can be successfully achieved through an optimum combination of technologies, markets and social and institutional mechanisms that suit a specific energy market.

Few comparative cost assessments for RE integration options have been presented in the literature. A European study of up to 20% wind energy penetration found additional power system operating costs to be around 10% of the total wind generation costs. However, a similar US study identified the additional costs to be more wide ranging, between 7% and 32% of capital expenditure for different power supply systems. The contrasting future visions for decentralised, small-scale, energy supply systems (“intelligent grids”) or large-scale, RE project integration, also make determination of future RE integration costs and potentials difficult. For RE heat, the additional cost of integrating biomethane into natural gas distribution systems can range between US$ 5-15 /GJ [TSU: figure will need to be adjusted to 2005 US$] varying with gas clean-up standards and whether transport is by pipeline or truck. For the transport sector, when and to what extent hydrogen fuel cell, hybrid biofuel, or electric vehicles might displace the current light duty vehicle fleet partly depends on the cost of developing the supporting infrastructure. Given all these uncertainties, further research and analysis will be required if useful integration cost data is able to be provided for scenario modelling.

Several risks and impacts involve the integration and deployment of RE. These include the sustainable use of land, water and materials, capacity building, technology transfer, and financing. For each of the transport, building, industry and agricultural sectors of the global economy, these risks are reasonably well understood, but no single integration pathway to gain increased RE uptake has been identified. Developing a coherent framework in preparation for higher RE penetration levels requires a good understanding of the diverse range of global energy supply systems.

- For the electricity sector, it is not possible to standardise on a single method for the transition from a traditional system to a highly flexible one. Whether large or small, each has its own particular governance, inter-connection, technology, market and commercial issues to deal with. In most systems, RE sources that do not fluctuate over the short term, and use mature technologies, are dispatchable and can be feasible as baseload options, in particular reservoir-hydro, geothermal and bioenergy. International experience of the integration of variable RE, mainly wind, has shown that high levels of penetration (>20%) can be feasible if facilitated by methods and investments that increase the flexibility of a conventional system. These include the provision of inter-connection between power systems, sufficient network infrastructure and capacity, system control and operation across the network, accurate forecasting, demand-side response, energy storage, more flexible thermal power plants and an enabling electricity market framework. To increase the penetration of RE resources, the stakeholders associated with a given “electricity system” will need to determine their unique pathway, whether the system serves a village or a continent.
- Transport presently has low shares of RE, mainly as liquid biofuels blended with petroleum products. Advanced biofuels are more fungible with petroleum production and distribution systems so once developed cost-effectively could encourage greater penetration. The on-going development of electric- and hydrogen-powered vehicles could enable utilization of a greater variety of RE sources available in a region. However, cost reduction challenges are evident and uncertainties remain concerning the source of the energy carriers, the related infrastructure and future technology developments.
- In the building sector, many successful examples exist of heating and cooling systems using biomass (for domestic cooking, space heating, district heating); geothermal (for high temperature process heat or low temperature ground source heat pumps); and solar thermal (for water and space heating, as well as for active cooling, at the domestic, community or district scales). Building-integrated electricity generation technologies provide the potential for building owners to become energy suppliers rather than just energy consumers. Integration of RE into existing urban environments, combined with efficient “green building” design, is key to further deployment.
- Integration of RE by the industrial sector is site and process specific, whether for very large, energy-intensive, basic material industries to numerous small and medium-sized processing enterprises. Direct fossil-fuel substitution on-site is often feasible (such as bioenergy for co-firing or CHP generation). For energy systems at the large industrial scale, RE is usually integrated with energy efficiency, materials recycling, and, perhaps in the future, CCS strategies. In addition, local industries can provide demand-response services for electricity supply systems (and in particular for future designs based around intelligent grids).
- Agriculture, ranging from large corporate-owned farms to subsistence peasant farmers, is a relatively low energy consuming sector, with pumping of water for irrigation and indirect energy for manufacturing fertilisers the greatest contributors. RE sources such as wind, solar, crop residues, animal wastes, are often abundant for the landowner to utilise locally or to earn additional revenue from exporting useful energy carriers (such as electricity or biogas) off-farm.

Integration across transport, electricity, building and industry energy supply systems is conceivable in the future, thereby creating a paradigm shift and a step towards an energy transition. Regardless of the energy systems presently in place, whether in energy-rich or energy-poor communities, increased RE integration with the existing system is desirable. The rate of penetration will depend on an integrated approach that will include life-cycle analysis, comparative cost/benefit evaluations, policy framing and recognition of the social co-benefits that RE can provide.

8.1 Introduction

This chapter examines the means by which larger shares of renewable energy (RE) can be integrated into energy supply systems at national and local levels. To enable RE systems to provide a greater share of global heating, cooling, transport fuels and electricity will require the modification of conventional power supply systems, natural gas grids, heating/cooling applications, and liquid transport fuel supply and distribution networks, so that they can accommodate greater supplies of RE than at present (Fig 8.1).

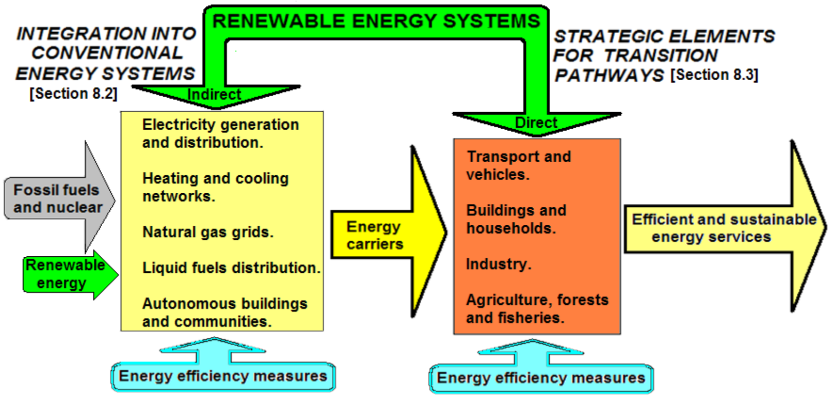

Figure 8.1: RE sources, additional to those presently being utilised in conventional energy systems, can be deployed indirectly through enhanced integration into energy carriers or directly on site by end-use sectors.

Overcoming specific technical barriers to increase deployment of a single RE technology are discussed in chapters 2-7. This chapter outlines more general barriers (including social ones) to RE integration at higher penetration levels and identifies possible solutions to overcoming them. Differences between geographic regions for the potential integration of RE vary with the current market status and the varying political ambitions of OECD and non-OECD countries. Diversifying supply by increasing domestic capacity, and by integrating a portfolio of local RE sources to meet an increased share of future energy demand growth, can make a positive contribution to improved energy supply security and reliability (Awerbuch 2006). Other than this and climate change mitigation benefits, RE systems can offer opportunities for sustainable development (Chapter 9), employment, improved health, and mitigation of supply risks from energy market instabilities, and hence improved security of energy supply. However, RE systems carry their own risks such as technical system failure, natural variation in resource availability from hourly to seasonally, price volatility, physical threats from extreme weather events, import dependence (e.g of biofuels), and relatively high capital costs under some conditions (IEA 2009).

Conventional energy systems are mainly based on oil, coal, gas, as well as nuclear, large hydro and traditional biomass. To achieve a rapid transition of the global energy sector away from the present dominance of fossil fuels will require uptake of more low carbon technologies. Nuclear power and carbon dioxide capture and storage (CCS) linked with coal- or gas-fired power generation as well as industry applications, will have a role to play alongside RE (Metz, Davidson et al. 2007). The transition of the energy sector will take time and involve significant investment costs (IEA 2009).

At present, the total shares of consumer energy supplied by RE systems remain low (Fig. 8.2). Shares in 2007 were around 16% of global electricity generation from hydro and 2-3% from wind, geothermal, bioenergy and solar; 1.5% of total transport fuels from biofuels; and 2-3% of total direct heating from solar thermal, geothermal and bioenergy (excluding domestic consumption of traditional biomass that accounts for around 10% of world primary energy) (IEA 2009). Annual average growth of primary RE between 2000 and 2007 was around 1.22 EJ/yr and could rise to 1.57 EJ/yr by 2030 under business-as-usual as shown in the IEA 2009 World Energy Outlook's Reference Scenario (*ibid)*. However, to make the necessary energy supply transition in order to achieve acceptable GHG atmospheric concentration stabilisation levels, the wide range of RE technologies will each need to continue to increase market shares out to 2030 as shown by the IEA 450 ppm Policy Scenario (Fig. 8.2), requiring an annual average rate of deployment growth at around 3.0 EJ/yr.

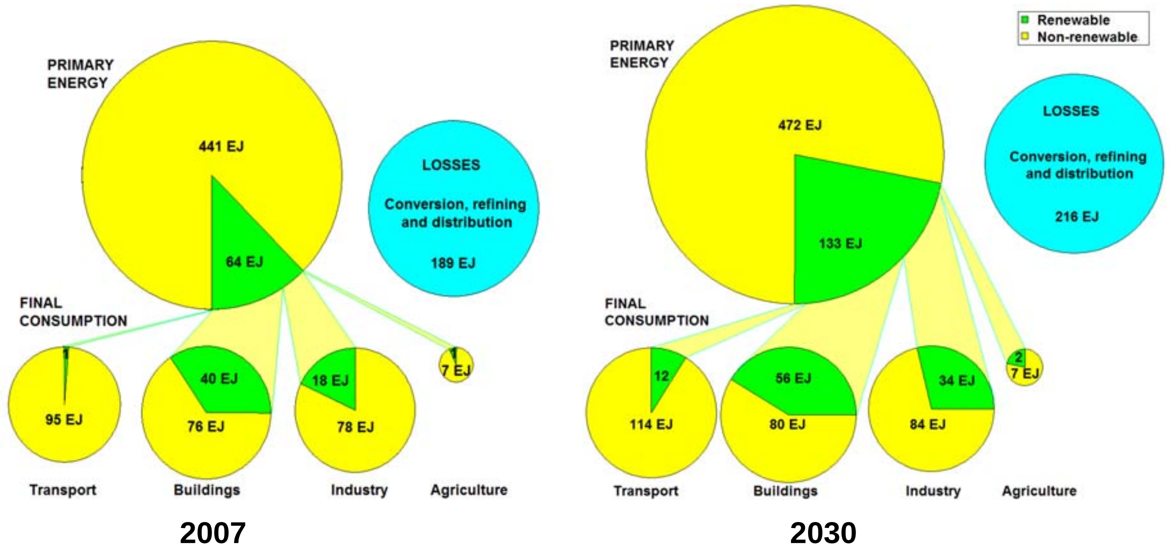

Figure 8.2: RE shares of primary energy and final consumption in the transport, buildings, industry and agriculture sectors in 2007, and indication of the increasing shares needed by 2030 to meet a 450 ppm stabilization target (IEA 2009).

Notes: Area of circles approximately to scale. "Non-renewable" energy includes coal, oil, natural gas (with and without carbon dioxide capture and storage (CCS) by 2030) and nuclear power. Energy efficiency improvements included in the 2030 projection. RE in the buildings sector includes traditional solid biomass fuels used for cooking and heating as used, along with coal, by 3 billion people in developing countries (UNDP 2009). This demand is projected to be replaced, in part, by more modern bioenergy systems by 2030.

Examples of successful integration of RE with conventional energy systems include both OECD and non-OECD countries such as:

- Brazil, with over 50% of light duty transport fuels supplied from sugar cane ethanol (Zuurbier and Vooren 2008);
- China, where two thirds of the world's solar water heaters have been installed (REN21, 2010);
- Denmark, with around 19.7% (7180 GWh) of total power in 2007 generated from wind turbines integrated with other forms of generation (mainly coal- and gas-fired) (DEA 2009);
- Spain, where the 2000 Barcelona Solar Thermal Ordinance resulted in over 40% of all new and retrofitted buildings in the area having a solar water heating system installed (EC 2006); and
- New Zealand and Iceland where the majority of electricity demand has been met from hydro and geothermal power plants for several decades.

It is anticipated that increased urbanisation will continue and that the more than 50% of world population living in cities and towns today, by 2030 will rise to 60% of the then 8.2 billion people (UNDP 2007). There is potential in many of these growing urban environments to capture local RE resources and thereby help meet an increasing share of future energy demands (Droege, Radzi et al. 2010). The potential exists to integrate RE systems into the buildings and energy infrastructure as well as to convert municipal and industrial organic wastes to energy (Chapter 2). However, existing local government planning regulations may restrict the deployment of such technologies (IEA 2009).

The required capacity, and hence cost, of a RE system will be less if it can be designed to meet a lower energy demand. Many energy scenarios show that a wide range of energy efficiency initiatives across the building, industry, transport and energy supply sectors will probably reduce future energy demand baseline projections significantly (Metz, Davidson et al. 2007). Whether reduced energy demand will encourage the greater uptake of RE over and above other energy sources is difficult to determine, but a lower demand could facilitate having a greater share of RE in a growing energy market (Verbruggen 2006). For example, before contemplating the installation of solar water heating, a wood pellet stove for space heating, or a small roof-mounted wind turbine for power generation, a building owner or developer should be encouraged to initially invest in energy saving measures and building design (IEA 2009).

Integration of RE into the energy supply system and infrastructure of many non-OECD countries today raises challenges that differ from those of OECD countries. A technology that is successful in one region may not be so in another, even where conditions are similar. There are significant regional and local differences in the potential and government support schemes (Chapters 10 and 11) with many developing country governments placing a higher priority on future economic development and security than on climate change mitigation, their major aim, as in India (MoP 2006) to supply electricity to the millions of people currently with limited or no access to modern energy services (UNDP 2009). The deployment of low-carbon technologies, particularly RE, could be a win/win solution (Chapter 9). Integration of RE into a new autonomous energy system in a rural region without energy infrastructure differs markedly from RE integration into regions which already have high shares of RE or where cross-border transmission options are possible. Small-scale, distributed, RE systems may be able to avoid the high capital cost of constructing infrastructure presently lacking (ARE 2009).

8.1.2 Objectives

A major objective of this chapter is to determine how problems of integration might affect the future deployment of RE technologies into conventional energy systems. For any given location, issues relating to a RE project can be complex as they can impact on land and water use; need to adhere to national and local planning and consenting processes; and require acceptance by the general public (as also would a fossil fuel, nuclear or CCS plant). Additional uncertainty results from some mature RE technologies failing to gain wider acceptance in the market, whereas others only close-to-market, are enjoying early integration into the energy supply system due to government support schemes. Co-benefits can drive governments to offer supporting policies (IEA 2008) (Chapter 9) regardless of relative costs. Many energy models have been produced that project how various energy supply sources could, together, meet future energy demands (Chapter 10). It is not the aim here to attempt to assess the potential rates of RE penetration or the future shares as a result of enhanced integration.

This chapter assesses the integration of RE into centralised, decentralised and autonomous, off-grid systems to provide desirable energy services (heating, cooling, lighting, communication, entertainment, motor drives, mobility, etc.). Regional differences between deploying various RE systems are highlighted, as are the barriers to deployment that depend on the system presently in place. Successful deployment depends upon the local energy resources, current energy markets, density of population, existing infrastructure, the ability to increase supply capacity, financing options and credit availability. The specific costs for each of the various technologies are covered in Chapters 2 to 7. It has not been possible in this chapter to accurately evaluate the future additional costs of system integration and deployment that modellers might wish, given the complexities, site-specificity, uncertainties and deficit of analysis in the literature (other than for wind, see Chapter 7). This poor understanding of integration costs is a barrier to wider deployment, so further analysis would be useful.

Ideally, energy systems need to be flexible enough to cope with future integration of the full range of RE technologies as they evolve. As market shares increase, competition between technologies as well as with incumbent fossil fuel-based technologies could result. Failing to recognise future competition can result in an over-estimation of the potential for any single technology. For example, if a local municipality supported the development of a large biomass-fuelled district heating scheme, existing solar and geothermal heating systems could become stranded assets. At the larger scale, should a large nuclear plant, or coal-fired power plant with CCS, be developed in a region to provide enough capacity to meet future electricity demand, then this would compete with investment capital and could potentially constrain the development of RE plants in the region for several decades, even where good RE resources exist. Similarly, for road transport, it is uncertain whether infrastructure for biofuel distribution for hybrid vehicles, electric vehicle recharging, or hydrogen production and storage will become dominant, or indeed if they will compete (section 8.3.1).

Factors such as technology experience cost curves, advances in existing technologies and RD&D developments are discussed in the technology chapters 2 to 7 that also examine issues of integration related to their specific technology. This chapter looks at the more complex cross-cutting issues relating to RE integration across technologies such as energy distribution and transmission through energy carriers, system reliability, energy balances, storage, system flexibility, ownership, project financing, market operation, supply security, social acceptance of the technology, public awareness, and providing a sense of independence. External factors such as future carbon and oil prices are covered in Chapter 10.

8.1.3 Structure of the chapter

Section 8.2 discusses the integration of RE systems into existing and future supply-side systems for electricity, heating and cooling networks, gas grids and liquid fuel distribution as well as autonomous systems. Where relevant, the integration costs and benefits of system design, technology components to facilitate integration, operation and maintenance strategies, markets and costs are discussed. The contrasting opportunities for small-scale distributed energy systems for heat, power and biofuels compared with large-scale district heating, high voltage, trans-continental, super-grid systems and liquid fuel pipelines are compared.

Section 8.3 outlines the strategic elements and non-technical issues needed for transition pathways for each of the transport, building, industry and agriculture sectors in order to gain greater RE deployment. The relevance of improved energy efficiency measures is included. The current status, possible pathways to enhance adoption of RE, related transition issues, and future trends are discussed for each sector. Major differences between sites and regions, as well as the different approaches necessary for centralised, decentralised and stand-alone RE supply systems, are assessed for both OECD or non-OECD countries.

8.2 Integration of renewable energy into supply systems

Conventional energy systems have evolved over many decades to enable efficient and cost-effective distribution of electricity, gas, heat and transport fuels to provide useful energy services to end-users. Increasing the deployment of RE systems requires their integration into these existing systems leading to more sustainable ones. This section outlines the issues and barriers involved as well as some solutions. It begins with the complexities of the various electricity systems operating around the world that differ markedly. Prerequisites for efficient and flexible energy conversion, mutual support between energy sectors, and an intelligent control strategy involve coherent long-term planning and taking a holistic approach to enable the whole energy system to provide electricity, heating, cooling and mobility. Electricity systems could ultimately become the backbone of future RE-based energy supply should an increase in global electricity demand result from a higher than anticipated share of "green" electricity being substituted for fossil fuel demand in the heating and transport sectors.

8.2.1 Electric power systems

"Achieving high penetration of renewable technologies with their variable generation characteristics will require many fundamental changes in the ways that electric power systems are planned and operated to maintain reliable energy service and to do so economically" (PSERC 2010).

Within a power supply system, some RE sources (such as reservoir-hydro, bioenergy and geothermal) are dispatchable whereas others (such as fluctuating wind, wave and solar PV) are non-dispatchable[1]. Efficient integration of large shares (generally above 20% but depending on the prevalent generation sources available for a specific power system) of these variable RE sources into an existing electricity generation system will require a major paradigm shift in the design and operation of a power system rather than making minor adaptations. This is an essential part of the transition from conventional systems with zero or very limited shares of variable, non-dispatchable generation together with a predominantly inflexible load demand, to more innovative systems encompassing high penetration of non-dispatchable plant, highly flexible generation plant, as well as flexible demand. Such a transition would need to be carefully managed over many years which could be a challenge, especially for countries with less political stability. Increasing the penetration[2] of RE in any given system will vary depending upon the existing plant and infrastructure, methods of operation, system flexibility and market design.

8.2.1.1 Features and structure of power systems

There are many textbooks and papers that discuss electric power systems at various levels of specialization (Freris and Infield 2008; El-Sharkawi 2009; Ummels 2009). This section therefore will provide only a brief summary of the issues relevant to RE integration. The overall aim of any power supply system, small or large, autonomous or inter-connected, is to balance supply with continually fluctuating demand at all times in order to avoid outages and maintain quality of supply (Box 8.1). The technical components (that are a subset of an electricity industry) include the processes of generation (converting primary energy forms in power stations into electrical energy), transmission (transferring electrical energy at high voltage over large distances up to 1000s of kms), distribution (transferring electrical energy at low voltage over local networks), and delivery to power end-use appliances that provide valued energy services. Consumers can, in principle, provide a proactive response by controlling at least part of their demand.

Most modern power supply systems have a portfolio of grid-connected generation technologies, often including large hydro and a relatively small share of other RE technologies, mainly wind, geothermal, bioenergy CHP and solar. The most common conventional "thermal" generation

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[1] The term non-dispatchable should be interpreted with care. In this report it denotes the characteristics of a variable RE source that at the system level can be dispatched to a major extent only by decisions of the system operator (for delivering positive and negative regulating power) if primary energy (wind or solar) is spilled (not used). Equally, if variable RE resources are not used in a must-run mode, primary energy will be spilled. There is always, however, a portion of "non-dispatchable" sources that can be dispatched, especially when used at a large scale, due to the correlation between load demand and the resource.

[2] Penetration of RE in a power system is the share of the total gross annual electricity consumption.

technology is based on steam turbines using coal, natural gas or a nuclear reactor to heat water and produce steam that spins the turbine connected to a generator. In a gas turbine, compressed air is passed into a combustion chamber fired by natural gas or oil and the hot compressed gas spins the turbine. Steam and gas turbine technologies can be linked in a combined-cycle plant by passing the exhaust gas from the gas turbine into a heat-recovery boiler to produce steam. Transmission networks have usually evolved within the boundaries of a nation or state before, in some cases, later becoming inter-connected to reach continental scale. They use specialized switches, transformers and overhead and underground cables to transfer electric current between generators and grid connection points to local distribution networks. Distribution networks convey electrical energy from the grid connection points to the premises of consumers. Embedded generation that is connected directly to the local distribution network is becoming more significant, especially for smaller scale RE generation.

8.2.1.1.1 Design and operation of power systems

Electricity supply involves a complex technological system made up of a vast number of individual components which may have many different owners and operators. Electrical energy is not storable in a cost-effective manner so special attention must be paid to the design and operation of the overall system (Box 8.1). Its operation requires managing second-to-second short-term fluctuations through to long-term horizons for the planning of future investments in new assets. Spinning reserve plants (usually hydro or thermal plants in part-load operation) are able to respond quickly to load changes as a contingency to help manage the short-term balancing of supply and demand and the quality (voltage, frequency) of electrical energy. These, and other network resources, provide ancillary services which can be used in the decision-making processes of power system operators for system security management and to provide system robustness and reliability (Billinton and Allan 1996).

Forecasts of future industry operations out to days ahead can be used to support security management and other operational decisions such as unit dispatch and unit commitment, and out to a year ahead for fuel purchasing, reservoir-hydro scheduling and planned maintenance of generation and network assets. Longer-term forecasts are used for planning system expansion.

Box 8.1: Principles of power balancing in the system

Power system operation covers time scales ranging from seconds to days and, within those timeframes, it is the responsibility of the transmission system operator (TSO) to ensure a continual balance between generation and consumption. The essential parameter is the system frequency (typically 50 or 60 Hertz (cycles per second)); if generation exceeds consumption at any particular moment, the frequency rises, and if consumption exceeds generation it falls. Small supply-demand imbalances occur all the time, and running or primary reserve is activated automatically to maintain power balance and a near constant system frequency. Large imbalances occur less often, for example due to the tripping of a thermal unit, the sudden disconnection of a significant load, or the tripping of a major transmission line. Secondary reserves are held to deal with such contingencies. In the event that these prove inadequate, automatic shedding of pre-determined load is used as a last resort to bring the power system back into balance. Failure at this point results in the disconnection of all generation leading to a system collapse or “black-out”.

Consumption of electrical power varies by the minute, hour, day and season, usually following a distinct load profile. Economic dispatch decisions for scheduling generation plants are made in advance as a response to anticipated changing trends in demand (while primary and secondary controls continue to respond to unexpected imbalances). Coal-fired, and some bioenergy and geothermal generators, require several hours to be started and synchronized to the grid, and for shutting down. These are usually run continually as base load, as are nuclear and also RE plant such as run-of-river hydro where operating costs are low due to no fuel requirements. Plant with more rapid response times, such as gas turbines or reservoir-hydro, are generally used for meeting peak loads as needed.

The TSO managing the balancing task normally has access to real-time information provided by major generators (such as plant output, state of readiness, planned maintenance), the electricity market and other players on consumption, inter-connector usage schedules, load projections and where RE becomes more important, forecasts of RE generation hours or even days ahead. Where wholesale electricity markets exist, power producers bid in at a fixed time ahead, (usually ranging from 5 to 60 minutes, or up to days when dispatching balancing reserve power). Bids are then accepted or rejected.

8.2.1.1.2 Electricity demand characteristics

Electricity load reflects user requirements for energy services and the characteristics of the appliances installed to deliver those services, such as heating, cooking, motor drives, lighting etc. Operating a large inter-connected power system differs from a small isolated system. Traditionally, the design and operation of a power system has been centrally managed by the TSO. However with the introduction of smaller scale RE generation embedded directly in the distribution network, this is outside the monitoring and control of the TSO. The continued growth of such generation alongside significant transmission-connected RE capacity, is leading to a reappraisal of the role of central power system control. It also highlights the need to move away from traditional system balancing, when load control is a last resort, to a situation where, to a significant extent, load is designed and controlled to follow available variable generation.

In analyzing and predicting demand behaviour, it is useful to group end-users into residential, commercial, industrial and miscellaneous categories. Residential and commercial consumers tend to have strong diurnal, weekly and seasonal patterns, but sensitive to weather conditions, whereas industrial consumption is usually steadier over time. Traditional residential electricity tariffs normally have few time-dependent characteristics and supply is regarded as an “essential service”. Therefore little attempt to date has been made to actively engage residential or small commercial end-users in electricity industry decision-making, for example to modify peak load demand curves by tariff design. For large commercial and industrial end-users, more attention has been paid to tariffs that result in active engagement in operation and investment decision-making, particularly for those who own and operate embedded generators. With the advent of electronic electricity meters and advanced communication and control equipment, more attention is now being paid to active end-user and embedded generator engagement (Lund 2007). This is reflected in the growing international attention being given to the concept of the “smart grid” (Schweppe, Tabors et al. 1980; Cheung 2010) that envisages coordinated, decentralized decision making involving all electricity industry participants. The concept could assist with wide scale RE integration but is only at an early stage of development (8.2.1.6). Critical evaluations are in progress as it may have unintended consequences as yet undefined.

8.2.1.1.3 Institutional and regulatory issues

Power systems were traditionally organized as either state-owned or privately-owned regulated monopolies within the borders of individual nations or states. Today, competitive electricity models first introduced in the early 1990s are becoming more common. A successful transition from a state-owned, monopoly to a competitive industry structure (usually with an independent regulator) can take decades. As a result, the transition to higher penetration levels of RE generation is often taking place in the context of a partially completed transition, thereby adding additional complexity and risks. In addition, transitions are also often taking place in the context of increasing international connectivity between previously independent power systems. This may allow additional RE generation to be successfully integrated but new forms of governance could add further complexity. From experience, market regulation is critical as countries well advanced in market development have suffered significant problems due to inappropriate regulation. It remains unproven whether markets can deliver stable low electricity costs to consumers and to this is added the challenge of moving power systems to a more environmentally sustainable basis.

8.2.1.2 Characteristics of RE generation

There are differences between RE and 'conventional' (thermal, nuclear and large hydro) generation plants since several RE generation types have distinctive characteristics that relate to large-scale integration as they cannot always be dispatched to meet changing demand. Understanding these characteristics, and their interaction and impacts with other parts of the power system, is the basis for successful RE system integration. A major issue is the additional imbalances potentially introduced by variable RE sources but these can be largely accommodated by various means to increase grid flexibility (IEA 2008). Typically, the technical characteristics of variable RE generation can differ from conventional generation with respect to variability and predictability; resource location; electrical conversion system characteristics and power plant capabilities.

8.2.1.2.1 Variability and predictability

The power output from variable RE generation such as wind, solar PV, concentrating solar power (CSP) without storage, tidal and wave energy systems (IEA 2008), fluctuates with the variability of the local resource. From a system operation point of view, they are therefore regarded as non-dispatchable. Their fluctuations can be predicted with various levels of accuracy but do not necessarily correlate with fluctuating power demand. Depending on the share of the total demand covered by variable RE, the increased variability and uncertainty in the power system may necessitate changes in system operation (8.2.1.3).

Analyzing RE variability at different time scales is necessary to understand and deal with the impacts on the power system (IEA 2008; Holttinen, Meibom et al. 2009). The variability time-scale for reservoir-hydro power, biomass, geothermal, ocean salinity and ocean thermal systems ranges can be seasonal to decadal, whereas solar and wind can vary within seconds (Fig. 8.3).

Figure 8.3: Time-scale of the natural cycles of RE sources (IEA 2008).

Over large areas, the aggregation of output from variable RE plants located over a wide geographic region is often small due to variations in the RE resource at any given moment (Giebel 2007). As a consequence the aggregated "smoothed" output of multiple RE generators can fluctuate less in fractional terms than that of individual plants (IEA 2008; Holttinen, Meibom et al. 2009). Hence, the frequently-used term "intermittent" for variable RE technologies is considered misleading as when aggregated at the system level and over different types of RE, the total output does not change instantaneously between zero and full power (such as is the case when a thermal or nuclear plant trips out). Rather, it varies at a rate dictated by meteorological and geo-physical effects (EWEA 2005; IEA 2008).

Experience has shown that integration and accommodation of variable RE resources in the system can become more manageable from the technical and economic perspectives if methods of predicting variability over short time scales (from a few hours to a few days ahead) are sufficiently accurate. Major improvements in the accuracy of short-term forecasting methods of wind power have been accomplished (Giebel, Brownsword et al. 2003; Kariniotakis, Waldl et al. 2006; Lange, Wessel et al. 2009), with beneficial consequences on integration costs. Aggregated PV and wind generation over a wide geographic area is more predictable as a result of the smoothing effect (3.5.4 and 7.5.2), whereas diurnal tidal variations are fully predictable being deterministic. Estimation of wave characteristics can be more certain than for wind speeds owing to their slower frequency of variation and direct dependence on wind conditions over the wave fetch.

8.2.1.2.2 Resource location

The broad locational characteristics of RE have consequences for distribution and transmission network infrastructure (8.2.1.3). Small-scale RE systems (such as small biogas plants, solar PV integrated into buildings, and run\-of-river hydro) can often be installed at or near the demand centre. Medium-scale wind, biomass CHP and hydro power plants are often widely dispersed over a network but can usually be located reasonably close to demand centres. Such distributed RE-based generation can bring advantages for some grids but can also pose new challenges, mainly requiring better controls, smart meters and intelligent grids (IEA 2009) (8.2.1.6). Large-scale RE systems can be more remote such as solar PV and CSP plants located in deserts, remote on-shore and off-shore wind, geothermal, forest biomass and reservoir-hydro plants. Where RE plants are installed in areas primarily linked to the location of the resource and away from the load or existing electricity networks, substantial new transmission infrastructure may be required.

8.2.1.2.3 Electrical characteristics and power plant capabilities

Electrical conversion systems, especially of variable RE systems, can be different from the classical constant speed, synchronous generator systems. Consequently, power quality characteristics such as power and voltage fluctuations, harmonic injections, active and reactive power control capabilities, and frequency response characteristics, can be different from conventional generators (Ackermann 2005). In addition, RE generation, (especially when connected through power electronic converters as are most new wind power and solar PV plants), does not inherently provide the rotating mass inertia of large conventional turbines that is important for stabilizing the grid in the case of faults or changes in frequency (DBCCA 2010). These differences have consequences on specific ancillary grid services (shared by conventional and variable RE generation), and on the specific connection requirements to be complied with by generators to give secure grid operation (8.2.1.3. Issues and challenges).

New technology innovations enable wind plants to function more like conventional power plants by meeting a major part of the control requirements made on traditional power plants, and by delivering ancillary services (Burges, De Broe et al. 2003). In a broader sense, experiences from different projects show that RE can give significant support for power system operation, especially by the creation of virtual power plants (VPP) (Styczynski and Rudion 2009) (8.2.1.6). However these capabilities are inherently linked, or limited to, specific technologies used, where the cost to deliver a specific ancillary service, and more generally to participate in the power market, is an important consideration (Jansen, van der Welle et al. 2007; Waltham 2009).

8.2.1.3 Challenges for integrating renewable energies

8.2.1.3.1 Impacts

The magnitude and type of impact that RE generation could make on a given power system are primarily dependent on the penetration level of RE. On several systems in the mid-term, this may reach more than 20-30% of total annual electricity demand (EWEA 2009) and in the long-term, up to 100% may be possible (Greenpeace 2007). Analyses for large-scale wind power integration (EWEA 2005; Holttinen 2008) provided an overview of the effects from increasing RE generation on a power system and indicated the possible contributions towards impact mitigation and power system support that RE might provide.

Impact studies on various power systems, both in time (from seconds to years) and geographical scales (from local to system-wide), have been undertaken for wave and tidal power (Khan, Bhuyan et al. 2008) and wind (Holttinen, Meibom et al. 2009). The summary for wind (Fig. 8.4) could be worthwhile considering when analysing the combined impacts on power systems for all types of RE. Higher levels of RE integration depend upon whether a given power system can successfully deal with these impacts and identifying in advance any specific challenges that should be addressed.

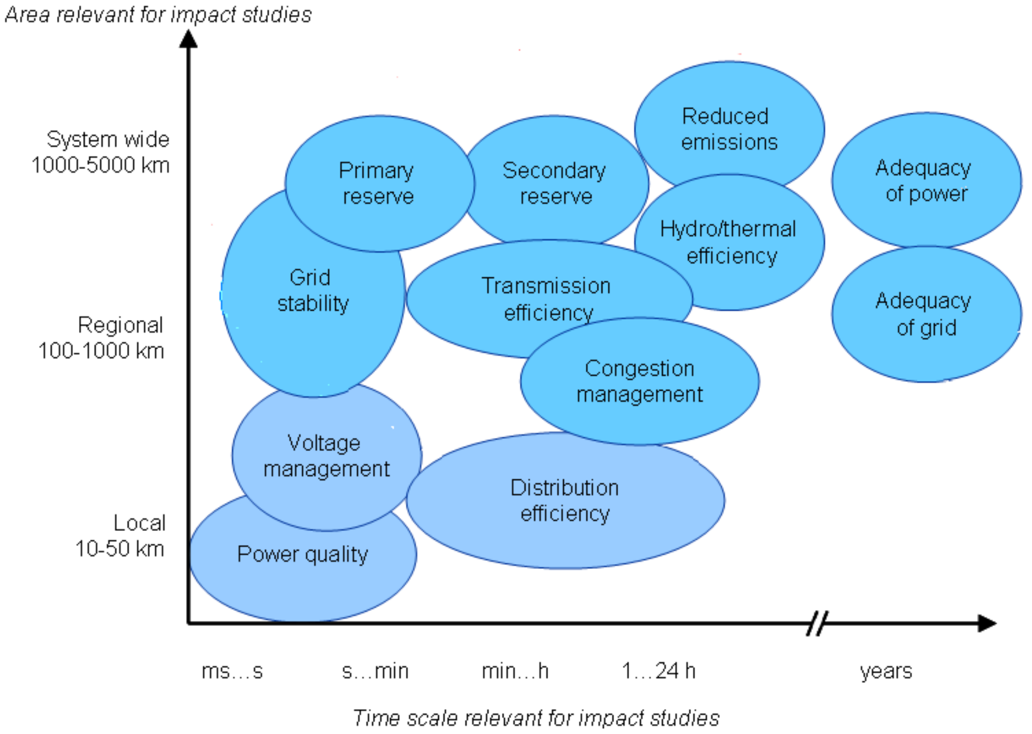

Figure 8.4: Impacts of wind power penetration on power systems by time and geographic area (Holttinen, Meibom et al. 2009), represent similar impacts from other variable RE sources.

8.2.1.3.2 Issues and challenges

The challenges brought by integrating variable and distributed RE systems highlight the need to address specific aspects of a power system. Integration issues have been analysed in several system studies, primarily for wind power to date, some for penetration levels reaching up to 50% (Eriksen and Orths 2008; EnerginetDK 2009). The experience with wind energy has more general relevance for other variable RE sources because it represents a challenging case in view of its high variability and relatively high penetration levels in some systems. There still is, however, a knowledge gap on integration issues for RE penetration levels higher than 20-30% of the demand. A current US project "The Western Wind and Solar Integration Study" is attempting to address this by studying the operational impact of up to 35% penetration from wind, PV and CSP (Lew, Milligan et al. 2009).

Based on wind energy integration experience (EWEA 2005; Holttinen, Meibom et al. 2009; Milligan, Lew et al. 2009), the main technical, economic, management and institutional challenges relate to:

- power system design, stability and operation at both generation and transmission levels;
- network reinforcement, extension and inter-connection of national and regional networks;
- network connection requirements for RE generation;
- system adequacy with high penetration of RE due to the low capacity value[3] (Giebel 2007) of several variable RE technologies; and
- electricity market design and corresponding market rules.

Power system design, stability and operation at the generation level

- *Increased reserve requirements* System balancing requirements (Box 8.1) are made more difficult by increased fluctuations and forecast errors, both of variable RE supply and load demand, since these are generally not correlated. This has consequences for the various types of system reserves in terms of additional capacity, plant efficiency and fuel requirements, and increased cycling of thermal plant. For wind energy, these effects have been analysed for several national and regional power systems up to penetration levels of 40% (Holttinen, Meibom et al. 2009). Fourteen studies from Europe, Scandinavia and US indicated increased reserve requirements in the order of 1-15% of installed wind power capacity were required at 10% penetration, and 4-18% at 20% penetration. With increasing penetration, there was no indication of a steep rise in additional reserve requirements and balancing costs. Deployment of a more flexible generation mix with increasing penetration of variable RE over time is expected to result in only a steady increase in integration costs (DeCarolis and Keith 2005). To meet a very large share of demand from RE by having a mix in a more flexible generation system, a knowledge gap remains concerning increased reserve requirements and costs.
- *Need for short-term forecasting.* An essential element when operating systems with a significant share of variable RE is accurate, short-term forecasting of wind and other variable RE sources (Kariniotakis, Waldl et al. 2006). This has been confirmed by experience in countries with significant wind power penetration including Denmark (Orths and Eriksen 2008), Spain (Giraut 2009), and Germany (Lange, Wessel et al. 2009). Such forecasts, numerical weather prediction data, power output forecasts etc. are used by TSOs, energy traders and plant operators to reduce costs and improve system security. Accurate forecasting also enables variable RE to be better integrated into the scheduling system and traded, whilst ensuring that demand and power supply remain in balance. Solar radiation forecasts for use by PV and CSP generators can give benefits similar to wind forecasts (Cao and Lin 2008; Reikard 2009).
- *Excess RE production.* Where RE output exceeds the amount that can be safely absorbed by the system to meet the current load while still maintaining adequate reserves and dynamic control, and where insufficient transmission capacity is available for export, a part of RE generation may have to be discarded (Beharrysingh and van Hulle 2009; Ummels 2009). To avoid spilling RE

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[3] The capacity value (also known as capacity credit) of variable RE generation in a power system is equal to the amount of conventional generation capacity that can be replaced by this capacity without diminishing the security of supply level.

requires taking operational and infrastructure measures as well as developing economic solutions for demand side management and control (8.2.1.6).

- *Ancillary services.* Apart from the balancing requirements, a power system requires other ancillary services (such as black start capability after an outage) to ensure operational security and system stability. RE plants can provide some of these services such as reactive power control (Burges, De Broe et al. 2003; Jansen, van der Welle et al. 2007; Styczynski and Rudion 2009), although if operating reserve is provided by variable RE, it is at the cost of lost production. Hence RE is not normally the first or most frequent option to deploy, especially at low penetration levels. Therefore appropriate equipment should be maintained in the system to provide the ancillary services that cannot be delivered by RE plants.

Power system design, stability and operation at transmission and distribution level

Increasing penetration of RE generation has implications for the operation and management of the network.

- *Management of transmission grids.* Specific combinations of RE generation and load demand in terms of penetration level and geographical locations, can cause changes in the magnitude and direction of power flows and differences between scheduled and actual physical flows in the transmission grid (EWIS 2010). Operational issues include the need for:
  - increased monitoring and forecasting to maintain sufficient network reliability;
  - improved congestion management;
  - voltage and reactive power management;
  - priority access for RE plants;
  - priorities for curtailment of RE in critical situations (for example during the combination of low demand with high RE generation); and
  - operating distributed RE generation in the event of transmission failures so as to keep at least parts of the system operational and hence avoid total black-outs.
- *Management of distribution networks.* Connection of RE generation to low-voltage distribution networks introduces similar effects as in transmission grids. These include changing direction and quantity of real and reactive power flows and harmonic distortion from the use of power electronic converters which may affect operation of grid control and protection equipment. In general, there is less active management of distribution networks than of transmission grids (Ackermann 2005; Lopes, Hatziargyriou et al. 2006). Nevertheless, distribution networks may have to cope with varying RE generation levels without reducing the quality of supply. Embedded RE generation has the potential to support weak distribution grids and improve power quality by contributing to grid voltage and quality control (Lopes, Hatziargyriou et al. 2006).

Network reinforcement, extension and inter-connection of national and regional networks

Transmission systems in several parts of the world have been confined within countries or to limited areas. National or regional TSOs and regulators traditionally deal with grid issues, balancing, and power exchange as determined by legislation, grid topology, geographical situation and historical developments. Evaluating the adequacy of transmission capacity to enable significant additions of RE generation needs to account for other factors traditionally not taken into account. These include locational dependence of the RE resources; relative smoothing benefits of aggregating distributed RE generation over a large area; opportunities for transmission optimisation created by combining different types of RE generation (GE_Energy 2010); and evaluating the transmission capacity required to access the flexible resources needed to manage RE variability.

Long term transmission planning to enable gradually increasing RE penetration levels is a complex process which has to proceed carefully through various stages.

- Relatively low penetration (<10%) of variable RE in existing networks could add to existing transmission congestion (Van Hulle, Tande et al. 2009; EWIS 2010). The extent to which transmission upgrades are required depends on the effectiveness of congestion management (see above) and optimization of the system, such as by the utilisation of dynamic line rating (8.2.1.6).
- At higher penetration levels, or in order to access new remote RE resources, new lines may have to be built. Several studies have identified the need for expansion of transmission systems to accommodate RE (Corbus, Milligan et al. 2009; Van Hulle, Tande et al. 2009; EWIS 2010; GE_Energy 2010). Planning methods are facing the classic 'chicken and egg' problem as for both transmission and RE power projects, the planning uncertainty of one is a risk for the other. An individual RE plant can be approved and built within one or two years whereas its transmission lines can take a decade to plan, permit, and construct. Public opposition to new transmission lines is expected to continue to be a major constraint for the integration of large amounts of RE in countries where public consultation planning processes exist (DBCCA 2010).

Network connection requirements for RE generators

Known as "grid codes", network connection requirements impose constraints on RE plants, just like on any other generation plants, in order to give system security, prevent negative impacts occurring on the network, and minimise operational threats to the power system as a whole. Where significant RE generation is being deployed, the specific grid codes for variable RE are continually being refined (8.2.1.6). Wind farms, for example, are now commonly expected to ride through faults, such as experienced at the point of grid connection during a temporary collapse of network voltage. They can also be expected to contribute to power system frequency regulation and local voltage support, as well as to limit power ramp rates that might make power system balancing difficult. This is to enable greater RE penetration whilst maintaining an adequate and reliable power supply.

Grid codes have been viewed as a hindrance to developing new variable RE projects, although they could be better considered as a prerequisite for ensuring efficient integration, even if less justified at very low penetration levels (Ciupuliga, Gibescu et al. 2009). Grid codes are country and system-specific, so result in a wide disparity of requirements that RE equipment manufacturers, developers and plant operators have to face across the globe. Internationally harmonized connection requirements for RE plants, (such as through the European Network of Transmission Operators (ENTSO-E) that was founded to coordinate network planning across Europe), could avoid unnecessary costs for RE plant manufacturers and operators (Ciupuliga, Gibescu et al. 2009).

System generation adequacy with high penetration of variable RE

Variable RE capacity can replace only a minor portion of conventional power plant capacity in the short to medium term, (although the generation share may not be negligible). Consequently, when deploying variable RE at a large scale, existing conventional thermal or nuclear plants may have to be retained in the system before gradually being replaced with more efficient and flexible dispatchable RE plants. Furthermore, generation adequacy at higher variable RE penetration levels, especially when aiming at 100% penetration in the long-term, needs to be supported with other integration solutions such as cross-border transmission, demand response and energy storage where cost-effective to do so.

Wind power experience demonstrates that the load carrying capability (capacity value) per unit of rated capacity of variable RE generation, depends on several system-related parameters and on the level of penetration (Giebel 2007; Holttinen, Meibom et al. 2009). In situations with low wind penetration but high aggregated wind power capacity factors at times of peak load, the capacity value can be as high as 40%. On the other hand at high wind penetration, the capacity value can be as low as 5% when regional wind power output profiles correlate negatively with system load profiles (Boyle 2007; Holttinen, Meibom et al. 2009).

Electricity market design and corresponding market rules
Technical solutions will not work unless matched by market design enhancements including market aggregation and close-to-real-time operation. For example, long gate closure times ahead of generation lead to larger forecast errors of both variable RE production and load demand. This results in higher balancing costs because forecast accuracy inherently decreases with longer forecast horizons (Kariniotakis, Waldl et al. 2006; Lange, Wessel et al. 2009). In a fragmented electricity market, balancing is more expensive than in a consolidated market where more balancing solutions are available. In addition, forecast errors can be reduced by the aggregation of uncorrelated, geographically dispersed, variable RE production (Holttinen, Meibom et al. 2009; EWIS 2010). Therefore, a re-design of market structures and procedures is a pre-condition if significant amounts of RE are to be integrated into national and international networks (Van Hulle, Tande et al. 2009; Waltham 2009). Case studies (8.2.1.5) and future options (8.2.1.6) provide further discussion concerning institutional aspects of RE integration.

8.2.1.4 Benefits & costs

In broad terms, the benefits of RE generation arise from:

- the displacement of fossil fuels, with ensuing reductions in fuel costs and external impacts such as GHG emissions and acid rain;
- reduced reliance on importing energy, under contract from either other power systems or other countries, thereby giving energy security and balance of trade benefits; and
- the development of a RE industry with ensuing benefits of employment, export earnings and the fostering of an innovation culture.

There is a lack of information in the literature on the costs of large-scale RE grid integration other than for wind power which is the most advanced in this regard. A roadmap for CSP systems with or without thermal storage (IEA, 2010), and a study of solar PV in RE system inter-connection (Kroposki, Margolis et al. 2008) provide some cost data. The investment and operating costs associated with integration of RE generation arise from:

- network augmentation to accommodate fluctuating electricity flows associated with variable RE generation;
- network extension to connect new RE power plants; and
- investment in, and operation of, complementary electricity generation, storage and end-use technologies that can respond in a flexible and efficient manner to the additional fluctuating energy flows associated with non-storable RE forms.

RE generation types with intrinsic energy storage, such as biomass, geothermal energy, reservoir-hydro, or pumped-storage power plants, behave in a similar manner to fossil fuel thermal generation and thus raise no additional technology-specific costs from being integrated into existing power systems except for context-specific connection costs. However, the situation is different for variable RE generation without intrinsic storage.

For large-scale integration of wind power, transmission network upgrades are often needed (Corbus, Lew et al. 2009; Holttinen, Meibom et al. 2009; Lew, Milligan et al. 2009; EWIS 2010). Various assumptions in the literature for estimated cost allocation, distance, and grid reinforcements vary widely with specific conditions (Holttinen, Meibom et al. 2009). This results in a wide cost range between US$ (2005) 100-200 /kW of rated wind power capacity for penetration levels up to 50%. However, where grid reinforcements benefit the whole system, their costs should not be allocated solely to wind power. Overall a fairly moderate increase of additional balancing costs can result from increasing wind penetration (Fig. 8.5).

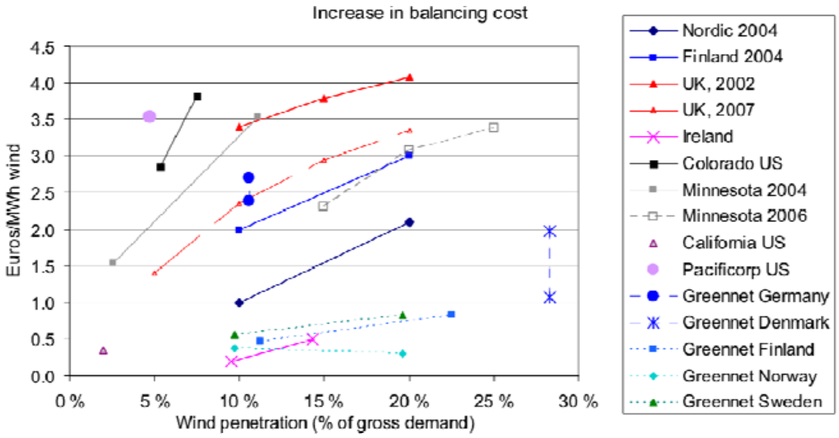

Figure 8.5: Additional balancing costs for the entire power system are higher at greater levels of wind penetration, as shown by several studies for sites in US and Europe (Holttinen, Meibom et al. 2009)

Note: Costs were harmonized using currency exchange rates of EUR 1 = GBP 0.7 = US$ 1.3 [TSU: Figure will need to be redrawn to present figures in 2005 US$]

Wind penetrations of up to 20% of gross energy demand were estimated to need additional system operating costs (arising from wind variability and uncertainty) for around 10% of the total cost of wind generation (Holttinen, Meibom et al. 2009), although a US study showed such additional costs were uncertain, ranging from 7-32% of capital expenditure based on installed costs around US$(2005) 1800 /kW (USDOE, 2008a). Large, unconstrained transmission regions, flexible complementary resources and efficient intra-day trading, are factors that can help to minimise the costs of wind energy integration (Holttinen, Meibom et al. 2009). Augmenting wind energy with high penetration of other RE technologies such as solar PV could help to smooth variability and thus also reduce overall integration costs.

Carefully chosen policies and commercial incentives may be required to bring forward an appropriate mix of “complementary resources” including generation, networks, storage and flexible end-uses, and to maximise the benefits that non-storable RE resources can bring whilst minimising the costs. For any given power supply system, the resulting generation mix, and the effectiveness of such a strategy, will be context-specific and need to evolve over time.

8.2.1.5 Country case studies - based on real experience of RE integration

Six case studies were chosen to demonstrate that different approaches to gaining increased RE deployment in national power supply systems are possible, but that there can be no single preferred approach as each situation depends upon the existing system design, local RE resource availability, current market shares and targets (Fig. 8.6), type of market, cost comparisons with conventional generation, and government policies.

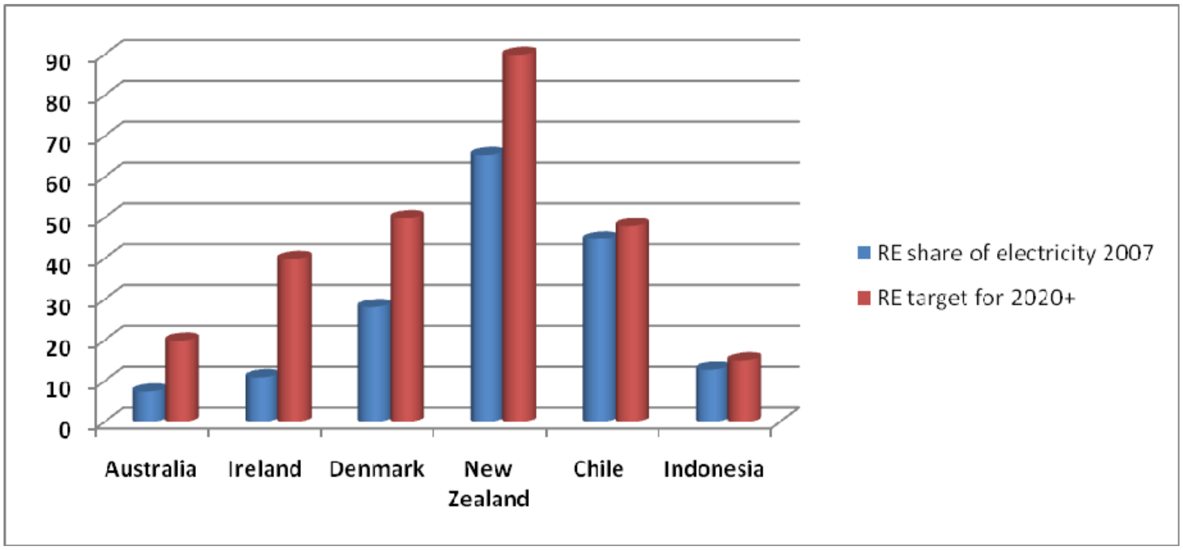

Figure 8.6: Current share of RE electricity generation and targets for countries selected (IEA 2008; ADB 2009; IEA 2009; IEA 2009).

Australia *–increasing the low RE share by market reform and inter-state connection.*

The Australian national electricity market (NEM) encompasses approximately 90% of Australia's 22 million population and about half its 7.7 Mkm^2 land area. NEM accommodates non-storable RE resources via a coherently designed decision-making framework that includes a real-time, security-constrained, 5-minute dispatch spot market, associated derivative and frequency control ancillary services markets (Outhred and Thorncraft 2010),, and a fully integrated wind energy (and potentially solar energy) forecasting system[4]. The market design is technology-neutral and based on concepts proposed in 1980 that foreshadowed high levels of RE penetration (Outhred and Schweppe 1980; Schweppe, Tabors et al. 1980). Wind farms connected at transmission-level can participate and compete with other generators for transmission access and to provide ancillary services. However, wind farm operators have to pay for ancillary services that they are deemed to incur.

The NEM has an annual energy of about 210 TWh, a peak demand around 35 GW, and with 1.9 GW of installed wind capacity and another 6.5 GW proposed by 2020. In the South Australian region of the market, wind supplied approximately 15% of the 13.1 TWh of electricity consumed in 2009 (ESIPC 2009) and at one stage reached 57% penetration with no operational problems. When wind penetration in the NEM is high, electricity prices tend to be low and vice versa, giving a disincentive to invest in additional wind farms but an incentive to invest in complementary resources (generation, storage and flexible demand) as wind penetration increases (Outhred and Thorncraft 2010). As a result the initial focus of wind developers in the South Australian region has now evolved into a broad pattern of wind farm development that provides more appropriate balance between the geographical patterns of wind resources and demand.

The Australian Energy Market Commission recently completed a comprehensive review of electricity and gas market frameworks in the light of climate change policies (AEMC 2009). It concluded that "the energy market framework is generally capable of accommodating the impacts of climate change policies efficiently and effectively" given some proposed changes including removal of retail price regulation (or at least greater regulatory flexibility), introduction of

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[4] See www.aemo.com.au/electricityops/awefs.html for the Australian wind forecasting system.

transmission charges between NEM regions, a regular review of the spot market price cap (presently approximately US$ 10,000 [TSU: figure will need to be adjusted to 2005 US$]), and the effectiveness of the reliability intervention powers of the Australian Energy Market Operator (AEMO).

Ireland – *increasing the low present RE share with limited inter-connection.*

Ireland published a national RE action plan in June 2010 under the European Renewables Directive (2009/28/EC), June 2009. The EU has an overall target of 20% of EU energy consumption from RE sources by 2020 with variations across member countries. Ireland's target of 16% RE for 2020 includes 40% of electricity generation (giving 10% of total primary energy consumption). As the vast majority of new RE capacity will be provided by on-shore wind, this target is a significant challenge for the Irish wind industry. By January 2010, the installed wind energy capacity had reached 1,264 MW accounting for approximately 11% of total electricity generation. So to meet the 40% target if by wind alone, an additional ~5,000 MW of capacity will be needed within the next 10 years.

The peak demand on the network is just over 5 GW with annual energy consumption around 28 TWh (Eirgrid 2009). The system currently has one HVDC connection to Scotland but has no synchronous connections to any other system, although a 500 MW HVDC link between Woodland and Wales is planned which could possibly reduce the wind constraints slightly. Approximately 45% (579 MW) of existing wind farm capacity is connected to the transmission system (>110 kV) with the remaining 55% (685 MW) connected to the distribution network (<38 kV). The maximum output reached by this portfolio of wind turbines was 1094 MW, occurring in March 2010. Wind has reached over 40% penetration on multiple occasions, once reaching 45%.

The governments of Northern Ireland and the Republic of Ireland commissioned an *All Island Grid Study* (DCENR 2005) to investigate the technical issues associated with the integration of high levels of RE generation and the resulting costs and benefits. It concluded that, if substantial investment in transmission reinforcement and the second inter-connector to Wales were undertaken, then RE generation equivalent to 40% of the total demand could be integrated into the system, delivering around 25% reduction of CO_2 emissions for a maximum of 7% increase in total system costs (DCENR 2005). The key challenges to successfully integrate this RE generation include the following.

- *Complementary portfolio* of non-renewable generation with the flexibility to complement the variable RE generation without excessive cost or CO_2 emissions and ensuring that the market and regulatory structures can facilitate the delivery and continuing commercial viability of the required plant.
- *System control* of the power system so as to ensure continuing stability and therefore reliability while facilitating the delivery of the RE.
- *Connection* applications for both RE and conventional generation received by the TSOs would be more than adequate to deliver the 2020 targets. The Commission for Energy Regulation has mandated a grouped connection process known as "Gate 3" to provide certainty for generation developers and to optimise network development (CER 2008).
- *Network reinforcement to enable* the connection of large amounts of new RE and conventional generation, the closure of existing fossil-fuelled generation and the development of new inter-connectors. EirGrid is implementing a grid development strategy to deliver the transmission required but there is a risk that opponents of constructing new electricity transmission facilities will delay implementation.

Since wind is a variable resource, it is recognised that in addition to a flexible plant portfolio, electric loads also need to be more flexible. Trials in smart metering and customer behaviour are under way using a sample of 8,000 dwellings which should enable a significant step forward to be taken in domestic demand side management. Electric vehicles (EVs) could complement wind generation by storing electricity and providing flexible demand. The Government has therefore set an electric vehicles target of 10% of the total by 2020 with 2,000 on the road by 2012 and 6,000 by2013 (DCENR 2010). The first recharging points have been installed in Dublin with 3,500 more scheduled to be rolled out across the country giving 2,000 domestic charging points and a further 1,500 on-street.

Denmark – *aiming to increase high wind penetration through a flexible energy system.*

The Danish TSO, Energinet, has investigated the consequences of doubling the present installed wind power capacity (~3,000 MW) before 2025 (Eriksen and Orths 2008; EnerginetDK 2009). About 2,000 MW is expected to be installed off-shore. Wind penetration could then increase from the current 20% of electricity consumption to 50%. The energy balance, fuel consumption, emissions, power balance, and the need for ancillary services and transmission grid upgrades have been assessed, as has the extent that integration of 50 % wind energy into the electricity system would place on system flexibility, the grid and load demand. The study confirmed that both domestic flexibility and cross-boundary power markets are pre-requisites for maintaining security of supply and maximising the economic value of wind power; connecting the power system to district heating schemes, the transport sector via electric vehicles, and energy storage systems would be vital for successful integration (Fig. 8.7); and a whole range of measures for generation, transmission, demand side and the market would be needed.

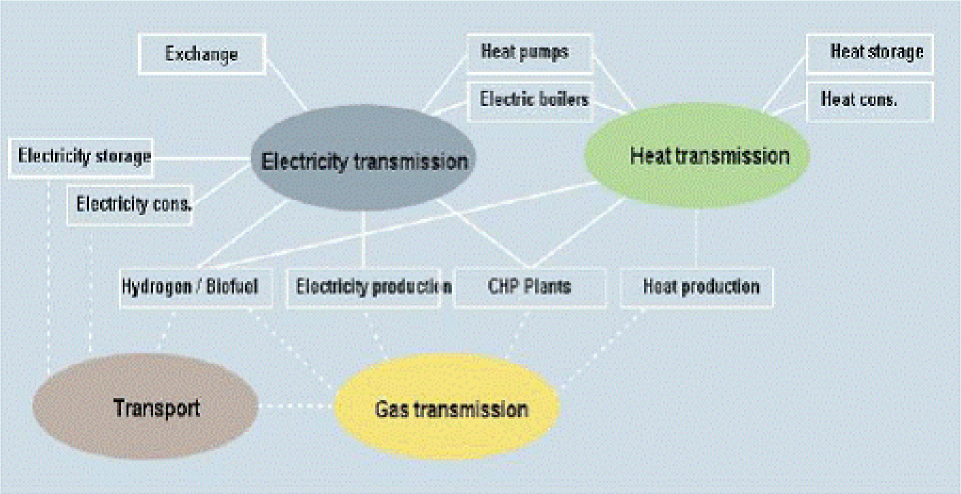


Figure 8.7: Possible linkages between the heat, transport, gas and electricity sectors to ensure successful large-scale wind power integration in Denmark (Eriksen and Orths 2008).

To prepare a coherent power system to support 50% wind penetration could need a holistic planning approach and modifications to the various sectors of the system as follows.

- *Generation*: a) Geographical dispersion of off-shore wind farms. b) Utilization of an electricity management system that regulates generation, mobilises regulating resources and new types of plants, and further improves local scale production units working on market terms.
- *Transmission*: Reallocation of grid connection points for off-shore wind power plants, increased grid transmission capacity, and reinforcement and expansion of the domestic grid and its inter-connections.

- *Demand*: Further development of price dependent demand; strengthening the coupling to heating systems (including electric boilers and heat pumps); linking the power system to the transport sector (using electric vehicles as a component of price dependent demand), and introduction of energy storage (possibly hydrogen, compressed air, or batteries).
- *Market*: Connection to the NordPool-EEX network to increase the possibilities of sharing reserves, improve intra-day trading possibilities and provide exchange of ancillary services.

These methods, investigated by the Danish TSO and partners to enable the required additional 3,000 MW capacity, would be applied over different time frames (EnerginetDK 2009).

New Zealand – *good RE resources leaving market to increase present high RE share*.

The New Zealand power supply currently generates around 67% from RE, varying in dry years. It is dominated by hydro (~55%) along with geothermal (~8%), wind (~3%), bioenergy (~1%), and solar PV (<0.5%) with the balance coming from gas and coal. In 2009, 43.7 GWh was generated from 8,508 MW installed capacity to meet the total demand of the 4.2 million population. A HVDC cable joins the North and South Islands with 1040 MW capacity north to south and 600 MW south to north. Inter-connection to Australia at 3000 km is impractical.

No supporting policies exist for RE plants which compete within the wholesale electricity market. Average retail electricity prices around US$(2005) 0.16/kWh domestic and US$(2005) 0.07/kWh industrial (including the fixed line charges spread across a typical year's supply), are higher than in Norway, similar to USA and Australia, but significantly less than those in Ireland, UK and Germany. Wind competes due to the high mean annual wind speeds giving capacity factors over 50% on some sites. Several wind farm and landfill developers, such as Palmerston North City Council, (IEA 2009) have sold carbon credits to support project costs.

The share of RE has declined steadily since 1970 due to the more rapid growth of thermal, partly as a result of reliability concerns during dry hydro years. Consequently, increases in CO_2 emissions have resulted, currently reaching around 280 g CO_2 /kWh (compared with Australia 860 g; US 570 g; Ireland 580 g; UK470 g; Germany340 g and Norway 5 g) (Yale 2008). The revised emissions trading scheme will add NZ$ 12.50 (US$(2005) 7.86) /t$CO_2$ to thermal generation when the power sector joins the scheme after 2011.

An analysis of power plants under construction, planned, or due to be decommissioned (IPENZ 2010), showed that to meet the projected 2015 total load demand of 48.8 GWh (allowing for projected improvements in energy efficiency), wind would rise to a 4-5% share, geothermal to 12-13%, hydro would decline to 46% with little increases from bioenergy, solar PV or ocean energy. By 2025, the 65% RE share of the 55.4 GWh demand would be met mainly from hydro (46%), geothermal (12.2%) and wind (8.3%). Wind industry analyses included other identified sites and showed the potential could reach 10.8 GWh (19.4%) (Strbac, Pudjianto et al. 2008). Even so, the government target to reach 90% RE by 2025 (Fig. 8.6) appears to be ambitious, although the possible contribution from rapid deployment of distributed generations systems has not been included.

As wind penetration increases, so does the need for additional peaking and back-up plant and the contribution of hydro to firm up wind power is reduced. To gain high wind penetration, higher peak capacity margins would be needed to maintain system reliability, ranging from 30% at 5% penetration in a dry year to 40% at 20% penetration (Strbac, Pudjianto et al. 2008). Hydro enhances the capacity value of wind (which is relatively high due to the high load factors). The total additional generation costs attributed to wind at 20% penetration were between US$ (2005) 5 - 7 /MWh.

Chile – *aiming to increase present limited RE share to provide energy security.*

Being the fastest growing economy in Latin America has resulted, in part, from the electricity sector becoming competitive following privatization in the 1980s. Since 1982 when only 38% of rural and 95% of urban households had power connections, this non-OECD country has successfully increased electricity access to almost everyone. With hydropower shortages now occurring every 2-3 years due to reduced precipitation levels, the shares of coal- and oil-fired power stations have increased (IEA 2009) leading to CO_2 emissions rising to 3.7 tCO_2/capita /yr (CNE 2008). The country depends on imported fossil fuels for 75% of its primary energy. Hence the government is consequently evaluating a more diverse mix of RE systems (along with nuclear and inter-connections) to provide enhanced energy security. The 4 800 km long country has three separate electricity markets. The Central system provides power to 90% of the 17 M population, has 35 generators, 20 companies owning 14,500 km of transmission lines, and 26 distribution companies. The spot market (with nodal pricing) usually sells at around US$(2005) 90 /MWh but this has spiked to around US$(2005) 320 /MWh during recent drought periods.

RE currently supplies around 26% of total final energy demand of which 70% is biomass, mainly used for domestic heating and cooking. Around 5% of power generation comes from 166 MW of on-site CHP installations and 40% from hydro (3393 MW reservoir-based, 1550 MW run-of-river and 159 MW mini-hydro at <20 MW scale). A further 433 MW of hydro capacity is under construction. The first wind farm was built in 2007, and 193 MW installed capacity is planned by end of 2010. The technical potential of wind has been estimated to be 1,500 MW, geothermal at 3,350 MW, solar PV and CSP at 40-100GW, mainly in the north of the country. Through diversification, RE could therefore reach 44% of electricity capacity by 2020 and become a key element of security, although more coal, LNG, diesel and fuel oil plants are also planned (Fig. 8.8).

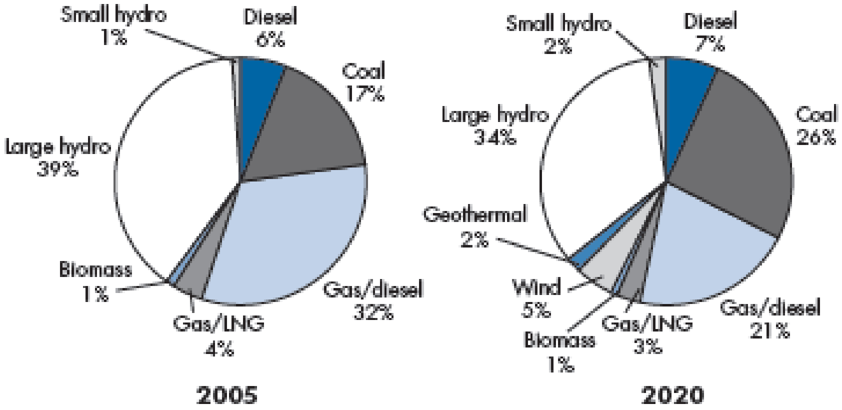


Figure 8.8: Projected installed capacity shares of power generation technologies in Central and North regions of Chile by 2020 (22.8 GW total) compared with 2005 (11.9 GW) (CNE 2008).

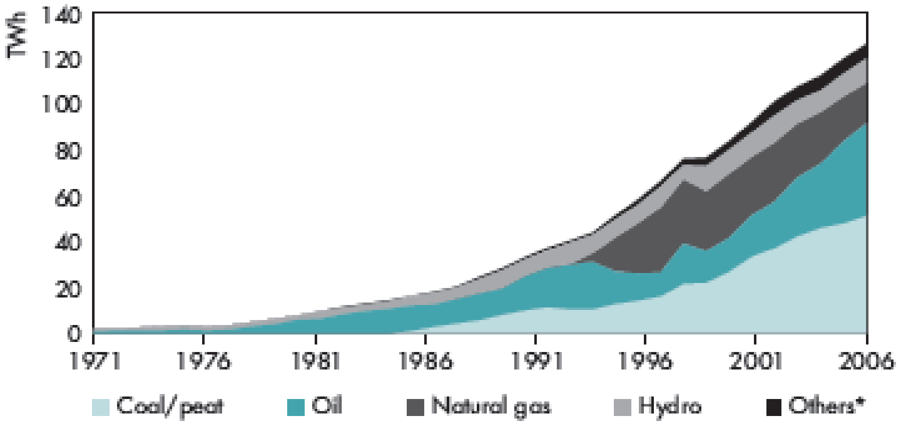
Accelerated deployment of private sector finance for RE is being sought by government along with training and R&D investments. Chile has been successful in securing finance from the Kyoto Protocol clean development mechanism (CDM) projects with 33 registered in June 2009 (36.2% for landfill gas, 17.4% hydro, and 10.2% bioenergy). Government policies to support more RE integration include penalties imposed on generators that do not secure sufficient back-up for dry years; exemption of transmission costs; rights to participate in the market regardless of scale; grants for pre-investment stages; sustainable geothermal concessions; tenders sought to build a 0.5W PV and a 10 MW CSP plant in the north; and an obligation that all generators are to produce at least 5% of total generation from non-hydro RE sources in 2010-2014, rising by 0.5% per year to reach 10% in 2024 and lasting till 2034 with penalties for non-compliance. To ensure this happens and that the expected 1400MW of new RE capacity by 2020 is built, electricity retailers will be established to give real competition and the TSOs given greater independence (IEA 2009).

Indonesia *–aiming to increase RE share to supply rural poor and reduce oil dependence.*

Energy supply to meet the demands of 200 million people living on Java, Madura and Bali and 40 million on 6000 other islands, is currently fossil fuel dominated, but good potential exists to increase the share of RE. In spite of good RE resources being available, around 35% of the population remain without electricity. Indigenous oil supplies are declining, energy demand is increasing, and there is severe poverty in rural areas that have poor access to energy services and high unemployment. RE could provide solutions as well as social and environmental benefits but will have to compete against coal and gas. Hydro power capacity is projected to increase by 2030 but its current share of electricity (8.4%) is projected to decrease to 4.3% due to rapid growth in coal- and gas-fired plants, whereas other RE generation, particularly geothermal could more than double to 11.9% (ADB 2009).

The lack of investment in electricity generation capacity and supporting infrastructure is resulting in demand exceeding system capacity, power restrictions, blackouts, transmission system failures, breakdown of generation plant, fuel supply disruptions and power quality issues. This is having a serious impact on the Indonesian economy, investment, and society in general. The state-owned utility, PT PLN, owned 86% of total capacity (24,887 MW) in 2006, with independent and private power producers the rest. Oil and gas dominated (Fig. 8.9). Current annual demand growth of around 8% requires around 3000-4000 MW capacity installed each year. In addition the government's target to supply 93% of the population with power by 2020 will add to the growing demand.

In 2005, around 12% (~15 TWh) of total generation was RE generated. Hydro had 4,200 MW installed capacity with around 72 GW potential and geothermal 1090 MW with 21 GW potential. Bioenergy (445 MW), small-hydro (<500 kW) (86 MW), solar PV (12 MW) and wind (1 MW) were mostly not grid-connected but have good potential in remote areas (MEMR 2008).



* Includes geothermal, solar, wind, combustible renewables and waste, etc.

Source: Energy Balances of Non-OECD Countries, IEA/OECD, Paris, 2008.

Figure 8.9: Electricity generation in Indonesia by fuel source from 1971 till 2006. [TSU: Figure will need to be redrawn as original and source listed in reference list.]

Energy price caps and subsidies imposed by government have kept electricity prices below market levels for many years so that power remains affordable for more people. Retail prices around US$(2005) 55 /MWh in 2006 were around half the average cost of generation. This policy has been costly to administer, constrained public and private investment, reduced the ability of enterprises to accommodate the cost of environmental compliance, and undermined energy efficiency and RE programmes (IEA 2008). The government has made major efforts to shift policy in order to accelerate the deployment of RE technologies into the marketplace, use locally available energy sources, create jobs and generate income in rural areas. However a new law (Indonesia 2009) that mentions prioritizing RE as a principle under the National Energy Policy "to ensure the sustainability of energy supply" outlines no means of so-doing. Phasing out price caps on electricity tariffs and fossil fuel subsidies have begun, together with an education campaign to explain why cost-reflective prices are now necessary. Establishment of a transparent independent regulator during the planned liberalization of the electricity industry has been recommended to provide incentives and clarity to investors on issues relating to the bidding procedure for new projects. Cost-effective RE feed-in tariff incentives, based on avoided costs as determined by the regulator, are proposed to attract the necessary investments and encourage continuing RE deployment. In the future the aim is for incremental costs of RE systems to be reflected in the tariffs to the electricity consumer rather than recovered from the government budget.

Currently, the 5 700 MW of RE technologies installed represent only 2% of the estimated technical potential (MEMR 2008). The current RE share of 4.3% total primary energy could rise to 17% (including biofuels) by 2025 with particular growth projected in geothermal capacity and decentralized power systems through local government initiatives together with local stakeholders. Financing may come from the regional government budget (especially for off-grid RE systems). The Ministerial Decree on Small Distributed Power Generation Using Renewable Energy was launched with the objective of promoting small-scale (<1MW) RE power plants by allowing enterprises to sell power to the local utility's power grid (where accessible). The challenge is to continue to give a strong focus to RE implementation by introducing cost-effective incentives that will attract the necessary investments to achieve the 2025 RE projection.

8.2.1.6 Options to facilitate the integration of RE

The necessary transition to a truly sustainable global energy supply system will be in the context of the increasing demand for energy services, partly driven by bringing populations within developing countries out of poverty. Integration of electricity from RE sources could become a dominant component of this transition and, in the long term, become the major energy carrier by also meeting loads for the transport and heat supply sectors. If so, challenges to the sector will be way beyond current knowledge or experience (Freris and Infield 2008). This section discusses how to manage integration challenges (8.2.1.3).

Assessing how to balance the power systems of the future across the range of relevant time-scales will be a major challenge. High levels of variable RE generation may not be schedulable[5], so matching supply to demand cannot always be achieved using conventional operational procedures developed historically. With more RE generation in the mix, together with potentially inflexible base load generation such as nuclear, it can be expected that flexible conventional plant would be needed for load-following and cycling. Most present systems have a significant proportion of generation coming from thermal power plants which if made more flexible, could assist TSOs achieve higher RE penetration levels. Co-firing of biomass with coal- or gas- fired plants is another RE integration option, that can be easy to manage in the power supply system and competitive depending on the delivered cost for the biomass (Chapter 2) and the investment cost for extra fuel handling equipment and boiler conversions (Rodrigues, Faaij et al. 2003). Many examples exist using blend levels around 5-10 % biomass by energy and there is future potential to link with CCS technologies and hence reduce atmospheric CO_2 concentrations. Experience and analysis leads to the following engineering and institutional approaches to electricity market reforms.

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[5] The term "dispatchable" used in 8.2.1.1 implies generation resources that can be dispatched by the power system operator to generate power at any specific time to meet demand, so here "schedulable" is preferred.

8.2.1.6.1 Engineering approaches

Technology options that could help solve the design and operation issues of reliability, stability and adequacy of a power system with high variable RE penetration include transmission design and upgrades, energy storage, demand-side control and centralized/decentralized energy management.

Transmission design and upgrades. In the short term, even at relatively low levels of RE penetration, transmission upgrades often coincide with methods for congestion management and optimisation of the transmission system. Technical measures that avoid or postpone network investments do not necessarily involve high expenditure. A number of technologies have significant potential to accelerate increased capacity as well as support RE implementation.

- Rewiring of existing lines with low sag, high-temperature conductors offers the potential to increase the overhead line capacity by up to 50% as the electrical current carrying capacity directly depends on the power line sag and the line temperature. Depending on the specific situation, rewiring may therefore be possible without the need for permit procedures, thus offering a fast method of transmission capacity enhancement.
- Dynamic line rating (DLR) monitors the temperature of existing power lines to prevent over-heating and therefore maximise transmission capacity. Solar power output tends to be highest during the hotter times of day when transmission capability is therefore lower. DLR can benefit solar since in many circumstances transmission line capacity limits tend to be conservative but can be exceeded if closely monitored. Since wind tends to be stronger at night and during cooler periods of the year, wind power output is highest when the lines are cooler anyway. DLR is already in use by the industry to give solutions to over-capacity, but standardisation of the method is required.
- Power flow control devices can help optimise utilisation of the grid. In large transmission networks there is often a physical lack of controllability which can lead to congestion on one transmission line whilst there is still capacity on an alternative line. Power flow control, installed in selected places, can ensure that existing transmission lines are utilised to the maximum and hence possibly avoid reinforcement of the present system and any associated planning difficulties (Van Hulle, Tande et al. 2009). Overloading of transmission components should not occur in properly engineered systems but, where it does, can be alleviated through an appropriate combination of power flow control technologies, system operation and expansion (Ye and Kazerani 2006). Voltage regulation technologies are fully commercialized but their performance can be further enhanced through R&D investment in power electronic devices (Xu, Yao et al. 2006).
- Increasing high-voltage, transmission capacity and coordination between different parts of an inter-connected system, enable more alternatives for TSOs to manage and help compensate for the variabilities of both demand and RE generation (Milligan and Kirby 2008). Transmission capacity expansion is most economic if planned for quantities of RE much larger than the size of an individual generation plant. So there could be rationale for planning, upgrading and building new transmission in anticipation of growth in RE, rather than to simply connect more new individual plants (Mills, Wiser et al. 2009) (though in politically unstable countries, such a long-term approach might be difficult). Proactive transmission expansion will vary depending on geography, the design of the existing power system, and the regulatory environment. The EU is considering ways to integrate RE particularly through improving transfer capabilities between TSOs by coordinating network planning through ENTSO-E (EASAC 2009; Smith, Holttinen et al. 2010).
- High voltage direct current (HVDC) transmission has potential for long distance, high capacity “highways” for example for large-scale RE integration super-grids. HVDC VSC[6] transmission

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[6] HVDC voltage sourced convertors (VSC) offer greater controllability than HVDC line commutate convertors (LCC).

technology offers advanced controllability over HVAC (Ruan, Li et al. 2007). On land, although it can be more expensive, point-to-point transmission over long distances is already used. HVAC undersea cables are presently the standard means of connecting off-shore wind farms to shore, but there are limits to the distances that can be accommodated (Bresesti, Kling et al. 2007). For connections where only subsea cables can be used, HVDC already out-performs HVAC over distances >100 km. As more off-shore wind and ocean energy capacity is installed (Bhuyan, Khan et al. 2010), meshed VSC-HVDC networks become attractive (Andersson and Liss 1991; Hendriks, Boon et al. 2006; Haileselassie, Milinas et al. 2008) to connect multiple plants to each other and possibly with multiple shore connections. This could also potentially be combined with, for example, providing capacity for trade of power between different market areas around the North Sea. Meshed HVDC networks are not yet an engineering reality and many technical issues need to be solved to provide effective network protection (Liu, Xu et al. 2003). However, various research teams are exploring different converter topologies and control schemes (Haileselassie, Milinas et al. 2008; Jiuping, Srivastava et al. 2008).

Energy storage. A range of energy storage technologies are available or being developed (EnergyPolicy 2008; Hall and Bain 2008; Inage 2009). Electricity cannot be stored so has to be converted to other forms of energy (chemical, mechanical, potential, heat, etc.) then later reconverted, when the electricity is required, giving efficiency losses. Storage is not economically viable for most power supply applications but if located near to a RE generation plant, it could help compensate for power flow fluctuations and, ultimately, voltage regulation (Molina and Mercado 2010; Suvire and Mercado 2010). Storage systems can provide instant response to demand fluctuations and, as a consequence, add flexibility to the system in terms of load levelling. There are many varieties of energy storage technologies (Table 8.1) but currently, they tend to be more expensive than reactive power control technologies, so are not used just to stabilize voltage. Pumped-hydro storage is a site-specific technology that could be deployed more widely than it is today but it is usually more costly than plentiful, low cost, reservoir-hydro that can provide storage. Compressed air energy storage is also site-specific but with only two plants deployed to date, in Germany and the USA (Chen, Cong et al. 2009). At the smaller scale, the lead-acid battery is widely used as an uninterruptible power supply resource but other technologies are under development.

Table 8.1: Technical characteristics of some energy storage systems (Chen, Cong et al. 2009).

Storage technology	Power rating MW	Discharge time*	Cost US$/kW	Energy density Wh/kg	Life years	Number of cycles
Pumped hydro	100-5000	1 to 24 h	600-2000	0.5-1.5	40-60	
Compressed air	5-300	1 to 24 h	400-800	3-6	20-40	
Lead acid battery	0.0001-20	secs to hrs	300-600	50-80	5-15	500-1000
Ni-Cd battery	0.0001-40	secs to hrs	500-1500	60-150	10-20	2000-2500
Lithium ion battery	0.0001-0.1	mins to hrs	1200-1400	200-500	5-15	1000-10000+
Vanadium redox flow	0.0001-0.01	secs to 10h	600-1500	10-30	5-10	12000+
Zn-Br flow battery	0.05-2	secs to 10h	700-2500	30-50	5-10	2000+
Flywheel	0.01-0.25	msecs - 15min	250-350	10-30	5-10	20000+
Super capacitor	0.0001-0.3	msecs – 15min	100-300	25-45	20+	100000+

Notes: *Short discharge times can be useful for uninterruptible power supply (UPS), power quality and reliability needs; longer times for energy management, load levelling, peak shaving and emergency back-up.

Not included are Na-S battery, Na-Ni-Cl (ZEBRA) battery, metal-air battery, polysulphide bromine flow battery, superconducting magnetic storage systems.

It is uncertain which, if any, of the alternative energy storage systems could eventually become commercially viable (Black and Strbac 2006). However, there are presently several generation modes where storage can at times be integrated beneficially, although not always cost-effectively:

- to compensate for a temporary loss of a generating unit in a conventional system (contingency reserve) and hence fulfil any commercial obligations for maintaining quantities of pre-sold electricity supply and avoid contractual penalties;
- to add value by improving RE generation predictability in order to obtain higher tariffs (e.g. wind for pumped-hydro to enable power to be dispatched during peak periods); and
- to minimise the running of back-up diesel generators in small-scale, autonomous, mini-grids and buildings that rely on variable RE sources and so often include battery storage.

In future, battery-powered and plug-in hybrid electric vehicles (8.3.1) could be used as storage for distributed energy systems (Kreith and Goswami 2007) depending on battery development to improve durability, economy and capacity for power control applications.

System level storage is not usually an economically attractive option in inter-connected power supply systems until high RE penetration exists (Holttinen, Meibom et al. 2009; Ummels 2009; GE_Energy 2010)(O'Malley, 2008). The requirement for energy storage should then be determined by the difficulty of balancing aggregated power supply with demand and the cost. In isolated power systems with high RE penetration there is a greater need for dedicated energy storage.

Demand-side control. Demand response (DR) is the time-shifting of power demand in response to an institutional incentive to improve demand/supply balance by responding to variations in RE generation. The power demand of heat pumps, electric water heaters, refrigeration units, and the charging of electric vehicles could all become responsive. Simple "ripple control" of electric hot water systems has been used for decades to reduce peak loads, but to enable wider control to be achieved, advanced metering infrastructure, energy management technologies, control interface technology for appliances used in buildings and factories, and information technology for communications are now available (NETL 2008).

Centralized or decentralised energy management. In order to manage more frequent and wider variations of RE generation, system monitoring of centralized or decentralised energy management is required to realize more robust power system control (Wang, Dou et al. 2007) and to improve system performance including rapid recovery from various system disturbances (Zhang, Xie et al. 2008).

Rural electrification involving RE generation requires a long-range view, the use of comprehensive planning methodology, and possibly involving the use of geographical information systems (GIS) (Amador and Dominguez 2006). This approach is more appropriate in OECD countries than in some developing countries where the key decision, based on a total life cycle analysis of the alternatives (Kaijuka 2007), is usually whether a particular rural community should be provided with an isolated off-grid, autonomous system (8.2.5) or be integrated into a larger power supply system by extending the grid.

8.2.1.6.2 Institutional approaches and market reforms

An electricity industry involves institutional decision-making for governance, security and technical regimes that differ from commercial regimes (Outhred and Thorncraft 2010). Institutional decision-making plays a key role in the long-term energy planning of regulated monopoly electricity industries but in competitive industries, such decisions may be delegated to a market that is supported by advisory functions. In either type of industry, systematic and coherent institutional decision-making can facilitate the integration of high-levels of RE generation. Tasks identified to facilitate high levels of RE generation in North America (NERC 2009), could be relevant elsewhere for either monopoly or competitive industries.

- Deploy advanced control technology designed to address ramping, surplus supply conditions and voltage control.

- Deploy complementary, flexible resources such as demand response, reversible energy storage and performance enhancements for non-renewable generation that can provide ramping and ancillary services to facilitate higher penetration of the variable resources.
- Enhance and extend transmission networks to move energy reliably from the new RE generators to demand loads and support the use of complementary resources.
- Improve market designs for energy and ancillary services to provide appropriate commercial incentives and penalties for variable RE and complementary resources.
- Enhance measurement and forecasting of variable RE generation output.
- Adopt more comprehensive planning approaches, from the distribution system through to the bulk power system.
- Explore further possibilities for inter-connection to extend the geographical scope of power systems that have high penetrations of variable RE generation.

At penetration levels above 20% on an annual energy basis, both the design and operation of a power system and electricity markets need new directions to give consistent policy decisions (Van Hulle 2009). Decision-making processes on grid reinforcement, technical standards, market rules etc. need to be well considered. In Australia, where a holistic approach to integrate non-storable RE resources into the national electricity market has been taken since 2003 (8.2.1.5), similar conclusions were reached.

A recent study on optimal wind power deployment in Europe (Roques, Hiroux et al. 2009) highlighted the need for more cross-border inter-connection capacity, greater coordination of European RE support policies, and electricity market designs and support mechanisms to provide local incentives. It has been suggested (Van Hulle, Tande et al. 2009) that integration of wind power had been constrained by planning and administrative barriers, lack of public acceptance, a fragmented approach by the main stakeholders, and insufficient economic incentives for network operators and investors to undertake transmission projects of European interest. The European Wind Integration Study (EWIS 2010) exemplifies an institutional approach to defining the tasks involved when integrating large amounts of RE generation.

8.2.1.6.3 Visions for possible future power supply systems

A number of speculative approaches to future power system designs have been suggested. These commonly involve a combination of:

- more highly connected power systems with greatly extended transmission infrastructure as, for example, are being planned in the EU (DLR 2005) and the USA (USDOE, 2008);
- ensuring loads, as far as possible, are temporally responsive to supply availability;
- making much greater use of distributed data collection, communication and control;
- employing adapted unit commitment, economic dispatch methods and short-term forecasts;
- improving management of distribution grids to cope with additional functions; and
- adapting market structures to combine balancing solutions and to provide incentives for building flexible generation capacity within the necessary time frames.

Integration of large-scale RE generation

In Europe, the projected growth of wind, wave and tidal stream capacity has raised issues of grid integration to a new prominence and highlighted the need for appropriate network reinforcement. In-feeds that vary over time need to be managed so as to maintain the reliability of supply, ensure that frequency can be properly controlled, and give confidence that the power system would be stable and robust in the event of faults. Specific technical challenges include dynamic matching of supply and demand (Smith and Kintner-Meyer 2003); local control of reactive power/voltage; robust and stable operation under abnormal conditions such as grid faults; and overall control of network frequency. Aggregation of the wind resource over a very large geographical area, and integrated with other RE sources, could result in firmer generation capacity. To date most studies that have examined such aggregation have been based on hourly data at best, and, although useful, cannot truly establish whether such power systems would be feasible.

Distributed generation

Traditional power systems have been based on centralised generation, designed to deliver power from large-scale generation plants in one direction to consumers (Fig. 8.10). This model is now being challenged by increasing levels of distributed generation (DG), such as CHP plants, wind farms, diesel engine gensets, or solar installations in buildings (IEA 2009) embedded in the local low-voltage, distribution network (Fig. 8.11). The possibility of DG completely taking over from centralised generation is unlikely to happen even in the long term, but integration of DG into existing supply systems could be technically feasible (Chicco and Mancarella 2009), as could autonomous DG mini-grids in remote rural areas or on small islands. Depending on the further development of the technologies and associated cost reductions, DG could make a substantial contribution to total power generation (ENARD 2010).

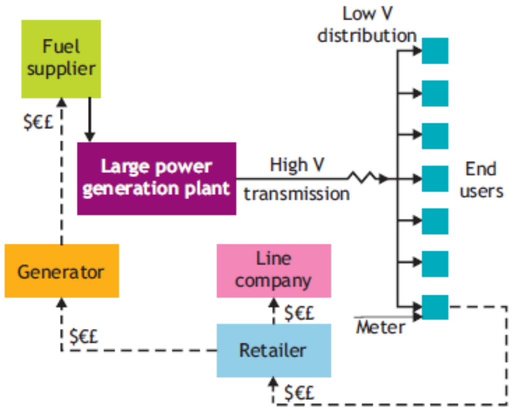

Figure 8.10: Simplified representation of a centralised power supply system with energy flowing one way (solid lines) and revenue the other (dashed lines) (IEA 2009).

Power systems can benefit from the aggregation of a large number of different generation resources and types of demand that together can help provide more reliable operation. Systems with access to tens or hundreds of different DG resources could potentially be less expensive than if attempting to provide the same level of reliability with only a few power plants (Awerbuch 2006). The benefits of aggregation could be accessed through a network and communication infrastructure that allowed for the transfer of power, and coordinated throughout the network with energy, revenue and information flowing in several directions (Fig 8.11). In a power system with high penetration levels of distributed and variable RE generation, to keep the supply-demand in balance it will be necessary to deploy innovative and effective measures such as ‘smart grids’ (Holttinen 2008), also termed ‘active networks’, ‘intelligent grids’ or ‘intelligent networks’. These still need clearer definition, further analysis (PSERC 2010) and demonstration.

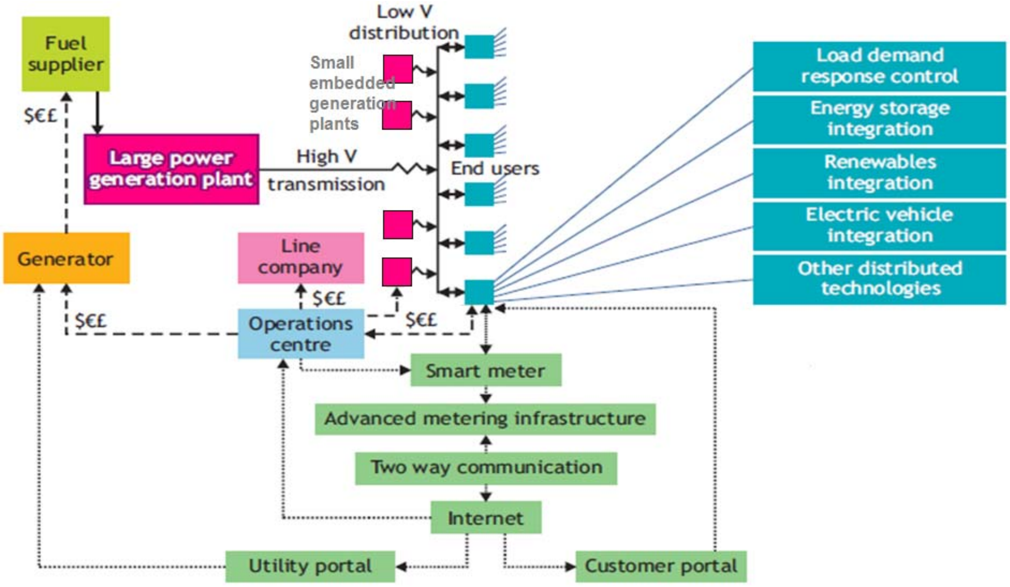

Figure 8.11: Simplified representation of a complex distributed generation system with two-way flows of electrons (solid lines), revenue (dashed lines) and information (dotted lines) through smart meters and intelligent grids (IEA 2009).

The EU has been investigating smart grid technologies under the European Technology Platform initiative since 2005 (Bouffard and Kirschen 2008). In the US, smart grids have been incorporated into energy policy by the Energy Independence and Security Act (EISA 2007) which promotes their development through a matching programme for states, utilities and consumers. The EISA has assigned the National Institute of Standards and Technology as the coordinating body for the development and modification of a number of standards that relate to smart grid interoperability (Molitor 2009). The US Department of Energy also commissioned a major “Renewable Systems Inter connection” study to address the challenges to high penetrations of distributed RE technologies (Kroposki, Margolis et al. 2008).

Projected growth in DG is prompting extensive research into the best way to integrate small-scale generation into the electricity system (IMechE 2008; Thomson and Infield 2008). DG is linked with related R&D investigations to explore the potential for low cost communication and IT infrastructure to improve the overall performance and cost effectiveness of power supply systems (Cheung 2010). In this context, the use of controlled, dynamic loads to contribute to network services such as frequency response, is now an active research area (Short, Infield et al. 2007).

As the generation sources become more distributed, co-ordinated system operation and control can become more problematic for TSOs. At this stage, there is no emerging agreement as to how such complex power systems should be designed and operated. Under certain fault conditions, particular power system dynamics can be excited and it is possible that the combined characteristics of a projected multitude of distributed RE resources might exacerbate these problems. If instabilities are detected, the challenge will be for control engineers to devise technically suitable and cost effective means of stabilisation. Dynamic control of the loads on the power system will become an increasingly important element as power systems evolve and accept higher RE shares to achieve improved environmental sustainability.

In a decentralized system, load demands could be harmonized with power system operation by information exchange together with energy management realizing demand-side control of residential or commercial buildings, or of an industrial area. As well as a means to balance an electricity system, a smart grid could, at least in theory, also provide power system stability and security of operation. Power production and consumption are monitored when supplying a load and the demand-supply balance would be maintained through an appropriate energy management control system (Van Dam, Houwing et al. 2008). A virtual power plant (VPP) is a combination of generation, monitoring and control technologies that could result in a business model akin to a single power utility. Distributed locations of substantial amounts of accumulated generation capacity can be regarded as a virtual single generation plant (see case study below).

8.2.1.6.4 Case study concepts for future power supply systems

Large-scale wind integration: European TradeWind
A study of wind integration across the power systems of Europe assumed a more highly inter-connected system than presently exists. It was undertaken between 2006 and 2009 by the TradeWind consortium and coordinated by the European Wind Energy Association (EWEA) with sponsorship from the European IEE Programme (Van Hulle, Tande et al. 2009). The aim was to investigate the adequacy of European power systems for large-scale wind integration. It assessed the options for improved inter-connection between European member states and the corresponding power market design needed to enable large-scale wind energy integration. Optimal power flow simulations were carried out with a European wide network model to examine the effects of increasing wind power capacity and, more specifically, of possible grid dimension situations on flows across borders. Future wind power capacity scenarios up to 300 GW in the year 2030 were investigated.

Simulations showed that increasing wind power capacity led to increased cross-border energy exchanges and more severe transmission bottlenecks, especially for the amounts of wind power capacity projected in Europe after 2020. The effect of passing storms on cross-border power flows was investigated. Wind forecast errors resulted in deviations between the actual and expected cross-border flows on most inter-connectors during a substantial part of the time and further exacerbated congestion. Significant economic benefits resulted from network upgrades that would relieve existing and future structural congestion in the inter-connections. A phased upgrade of 42 inter-connectors would benefit the European power system and its ability to integrate wind power, and lead to savings in operational costs of €1500M /yr (US$(2005) 1730/yr), thus justifying investments in the order of US$(2005) 25.4 billion for wind power up to 2030 (Van Hulle, Tande et al. 2009).

The project specifically examined the benefits of trans-national, off-shore grid topologies for the future integration of wind power. A meshed grid linking 120 GW of off-shore wind farms in the North Sea and Baltic Sea to the on-shore transmission grid, compared favourably to the alternative of radial connections of individual wind farms. This was due to higher flexibility and the benefits it offers for international trade of electricity. The study assumed further upgrades of the on-shore network but this will need further evaluation (EWEA 2009)[7].

Aggregating wind energy production from multiple countries strongly increased the capacity value in the system: the greater the geographic area, the higher the capacity value. When comparing a situation with and without wind energy exchange between the countries, the relative increase of capacity value was found to be 70%.

The TradeWind project also evaluated the effect of improved power market rules in terms of reductions in the operational costs of generation. The introduction of intra-day markets for cross-border trade was found to be of key importance for market efficiency, leading to savings in system

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[7] EWEA has proposed a long-term plan for off-shore grid development. The technical, economic and regulatory options for such a grid delivering 12% of Europe's demand are further researched in the IEE Offshore Grid project (www.offshoregrid.eu).

costs in the order of US$(2005) 1.15-2.30 billion /yr compared to a situation where cross-border exchange must be scheduled a day-ahead. To ensure efficient inter-connection, costs should be allocated directly to the market via implicit auction.

Intra-day rescheduling of the generation portfolio, taking into account wind power forecasts up to three hours before delivery, resulted in a US$(2005) 300 /yr reduction in operational costs (compared with day-ahead scheduling). This was due to the decrease in demand for additional system reserves. Consequently, the TradeWind analysis recommended intra-day rescheduling of generators and trading, a consolidation of market areas, and increased inter-connection capacity in order to enable more efficient wind power integration.

Large-scale RE power integration - Desertec

The "Desertec Industrial Initiative GmbH" was initiated in 2003 by the German Club of Rome global think-tank. In 2009, a consortium of 12 German and Spanish engineering, financial and energy companies launched a US$(2005) 500 billion investment assessment scheme with the aim to produce 15% of Europe's electricity demand in 2050 (Global_Insight 2009). The concept aims to harness solar energy from the desert areas of Middle East and North Africa (MENA) using mainly concentrating solar power (CSP) spread over nearly 17,000 km^2 and inter-connected with wind and hydro generation plants (Fig. 8.12). Transmitted to Europe through HVDC cables and the reinforcing of existing transmission lines, the project theoretically could enable the present 16% share of RE electricity in Europe to rise to 80% in 2050 (Trieb and Műller-Steinhagen 2007). Provision of water supply through desalination is part of the concept (DESERTEC 2009). The locations of the curved solar mirrors, turbines and solar thermal storage systems of the CSP plants are yet to be decided. The usual water demand for CSP cooling towers could be replaced by dry air cooling (or hybrid wet/dry cooling) but with an efficiency penalty (IEA, 2010). The venture is in the very early stages of evaluation with major technological, fiscal, logistical and political barriers yet to be overcome.

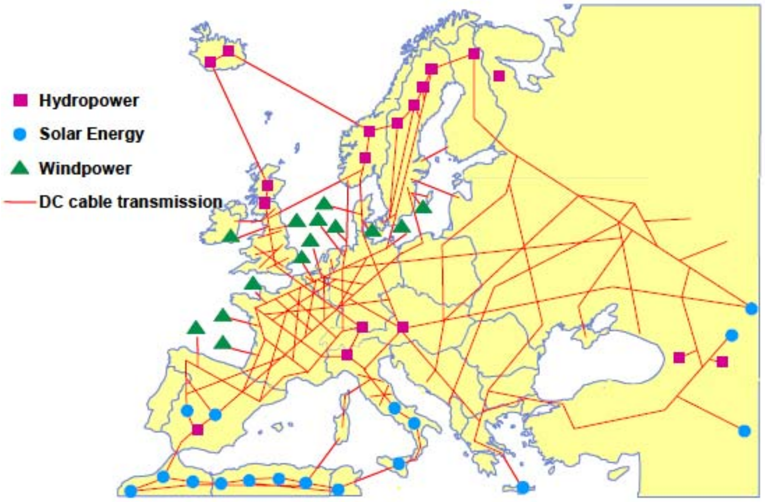


Figure 8.12: The concept of an inter-connected electricity grid between Europe, Middle East and North Africa based on HVDC transmission "highways" to connect with the existing AC grid and other power plants (Asplund 2004).

Around 85% of the projected investment cost will be for the CSP plants and the remainder for the 20 or more new transmission cables. One partner, Abengoa, has experience of developing CSP demonstration plants integrated with natural gas, combined-cycle plants (Abengoa 2010) including:

- a 472 MW plant in Ain Beni Mathar, Morocco of which 20 MW is CSP from 183,000 m^2 of parabolic troughs; and
- a 155 MW system in Hassi R'Mel, Algeria of which 25 MW is a parabolic CSP system.

The share of electricity generation from the CSP is likely to remain relatively small at this stage since establishing commercial-scale CSP facilities has been constrained by their relatively high cost at around US$(2005) 120-330/MWh (IEA, 2009a). However, there is an expectation that these costs will decline to US$(2005) 70-200 /MWh by 2030 (IEA, 2009a).

The electricity demand of MENA nations is projected to rise over three times by 2050 from around 1000 TWh/yr today, with a further 500 TWh/yr probably needed for desalination to meet the projected water deficit (Trieb and Műller-Steinhagen 2007). Therefore the concept of exporting power from the region may prove difficult to promote. There is also unresolved debate whether improved energy efficiency measures and the advent of DG (including solar PV) will be a cheaper option than investment in the Desertec project infrastructure and upgrading the existing transmission networks throughout Europe (Global_Insight 2009). Further analysis is warranted to assess the combined effects and costs of integrating a wider portfolio of RE.

Until 2012 the Desertec consortium will concentrate on accelerating the implementation of the concept by creating a favourable regulatory and legislative environment and developing a plan for development (DESERTEC 2009). It will consider how to manage the political issues, ensure the technological barriers can be overcome, assess whether the CSP plant components can be manufactured at the rate required, and evaluate whether transmission losses can be kept low enough to make the venture profitable.

Another similar concept, the Meditarranean Solar Plan was established by Mediterranean countries in 2008. It also intends to export electricity to Europe from 20GW of RE (mainly CSP and wind) installed in the south and eastern parts of the Mediterranean basin (Lorec 2009). Several North African states already have solar targets for the medium term and in Algeria and Morocco feed-in-tariffs are in place.

Renewable virtual power plant

This combined RE power plant system concept, an initiative of several German manufacturers of RE technologies, aims to demonstrate the feasibility of using RE to meet 100 % of electricity demand by producing a model virtual power plant (VPP) and hence dispel the major arguments against a major penetration of RE, including variable generation, poor predictability and lack of controllability (Mackensen, Rohrig et al. 2008). The project is supported by partners from the RE industry and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) based at the University of Kassel, Germany. A prototype computer model has been in operation since May 2007.

A VPP can consist of numerous decentralized RE generating stations, as well as storage devices and non-RE power plants).These are combined by means of a central control unit (CCU) consisting of system management, forecasting and primary controls (Arndt, von Roon et al. 2006). The VPP combi-plant model uses only existing RE technologies and is designed to represent a future scenario for meeting the annual electricity load of a small town of 12,000 households. The first step in creating this 100% RE scenario was to estimate the wind, solar PV and biogas potentials. The system then aggregated and controlled the power generation from three distributed wind farms (12.6 MW total capacity), 20 solar PV plants (5.5 MW total), four biogas-fired CHP plants (4.0 MW total), and a 1.06 MW pumped storage hydro system (Fig. 8.13) in such a way that the output matches the varying specified load at all times. The assumed capacities and outputs of the system components reflect current technologies and made it possible to compare the model results using real power plant output data. The total electricity produced (including imports/exports and storage losses) was 43.5 GWh /yr (with around 60% from wind, 15% PV and 25% biogas). Around

10,000 such VPPs would therefore be needed to supply all of Germany (Mackensen, Rohrig et al. 2008).

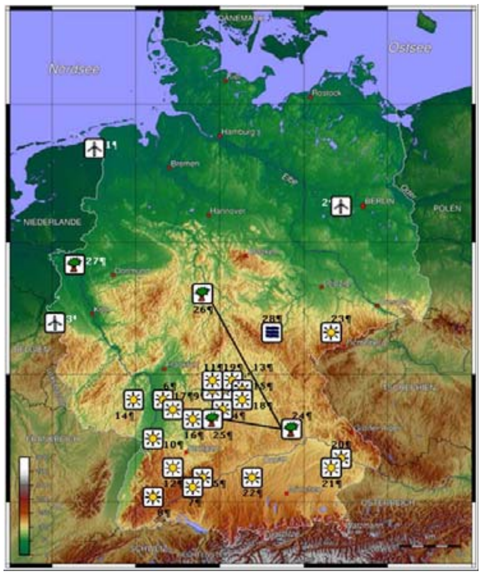


Figure 8.13: Technology components used in the German renewable VPP model are wind (1-3), solar PV (4-23), biogas (24-27) and pumped hydro (28). (Mackensen, Rohrig et al. 2008).

The variable wind and solar power components were geographically spread in order to take advantage of smoothing effects due to different weather conditions experienced at any given time. These were combined with dispatchable biogas-fired CHP outputs and the pumped-hydro storage reservoir. All the generation plants in the assessment are real and currently feed electricity into the public grid. The pumped-hydro storage device has yet to be developed (Mackensen, Rohrig et al. 2008).

The use of intelligent control, regulation technology and forecasts enabled the decentralized installations to be linked together so that fluctuations in the amount of electricity fed into the grid could be balanced. The CCU balanced the various output forecasts and measurement values. Based on the data (Mackensen, Rohrig et al. 2008), the control process was carried out in two steps.

- *Forecast and scheduling*. The CCU received weather and demand forecasts. Based on these, it anticipated the amount of power to be produced by wind and solar plants (Rohrig 2003). To balance the difference between the anticipated demand and the electricity generated by wind/solar energy, the CCU calculated a schedule and sent it to the biogas plant operators. A surplus or shortage was balanced out by using the pumped-storage power plant and, as a last resort, by exporting and importing to and from neighbouring grids.
- *Comparison of actual data*. The CCU received feedback from all the power plants on the actual real output and compared this data with the immediate demand. Differences compared with the forecast values were balanced through short-term adjustments to the biogas electricity outputs within minutes. The algorithms created for the concept were verified.

Running the model showed that to deal with a large portion of fluctuating power, it was necessary to install more total capacity than was needed at peak load demand. The VPP needed some storage capacity to be able to constantly meet the demand. When supply exceeded demand, the surplus could be shed, stored or exported to neighbours through ENTSO-E. Exporting electricity led to additional costs for grid reinforcement and expansion. Creating new storage capacity also involved a cost and storing and transmitting electricity always resulted in losses.

At higher penetrations of fluctuating RE sources, intelligent integration into the supply system was required to balance production with demand. Integration into electricity markets required an adequate payment system to replace the existing fixed tariffs as defined by the German Renewables Act, 2000 (EEG). A bonus payment for cogeneration or storage would allow transfer of the responsibility for compensating for variable generation to the producers. Under the existing law and the fixed tariff system, neither operators of RE plants nor TSOs have incentives to actively seek steady production, links with demand side management, or integration of storage devices. Valuable opportunities that arise when selling electricity on the free market appear more often because of rising prices and the declining tariffs of the EEG. The analysis confirmed that the concept could supply Germany (inter-connected with the European Union for the Co-ordination of Transmission of Electricity) with 100% renewable electricity but to achieve this will require R&D investment, political will and societal support.

Distributed generation (DG) - Danish project

The Danish TSO, Energinet, commissioned a Cell Controller Pilot Project (in association with the owners of wind-turbines and local CHP plants) with the aim of developing controllers, data acquisition, commands, and communication infrastructure for a pilot "Cell". Evaluating the co-ordinated, intelligent control and integration of a DG grid was the objective. The Cell consisted of existing distributed assets including four 1 MW wind turbines, a 2 MWe and 8.8 MWe bioenergy co-generation facilities, and approximately 5 MW of residential and commercial managed loads. Test stages covered three areas of rural Denmark, each with wind and bioenergy cogeneration sites and with local villages linked by 150/60 kV distribution lines.

When a significant number of RE generation units are located within a low voltage distribution grid, special attention has to be paid to the coordinated planning and operation of the transmission and distribution networks. More intense use of the grid in order to co-ordinate greater shares of variable RE generation can lead to a reorganization of traditional structures and operational procedures. Revised architectures for power system control ("intelligent grids") are needed for the active control of such distributed resources (Orths and Eriksen 2009).

Operation of the Cell was possible on a live power system. The primary functions of the Cell controller were:

- to manage the intentional islanding of the Cell from the transmission system;
- to assess the Cell's continued operation using local, distributed generation;
- to analyse resynchronization problems of the Cell with the grid; and
- to control a combination of distributed assets as a VPP in grid-connected operation.

The Cell controller was first tested in a power system laboratory environment in order to validate all control algorithms and communication methods. The pilot-stage Cell was then deployed over a 100 km^2 area and the first comprehensive field tests undertaken in 2008 to assess support transmission operations during emergency conditions and to enhance market-based control over the assets during normal operations (Martensen, Kley et al. 2009).

The controller and its supporting equipment maintained the intentionally islanded Cell from the grid, meeting grid code requirements in all cases. The Cell was also successfully resynchronized with the grid. Based on these results, over 40 wind turbines and five CHP units will be added to the pilot Cell's asset mix and the controller will be further developed to give emphasis on modularity and scalability and the inclusion of new functionalities, such as an expanded virtual generator control.

Examples of how the Cell project may benefit transmission and distribution companies include:

- each Cell being regarded as a VPP with the same or better controllability compared to a single traditional power station unit of similar capacity;

- local distribution companies attaining active distribution network on-line monitoring and control;
- automatic transition of a Cell to controlled-island operation in case of imminent transmission system break-down;
- black-start of the transmission system; and
- robust Cell controller designed to encompass all new types of DG units and controller functionalities (Martensen, Kley et al. 2009).

Energinet.dk and the Danish grid companies expect to obtain valuable knowledge through the completion of the project to encourage them to continue the long-term process of redesigning the Danish power system, thus enabling optimum integration of the growing volumes of local power generation. The major share of generation will come from wind and other RE sources. A control structure enabling intelligent and optimum utilisation of existing and future distributed generation resources through distributed control technology should result (EnerginetDK 2008).

8.2.2 Integration of renewable energies into heating and cooling networks

8.2.2.1 Characteristics

A district heating or cooling (DHC) network allows multiple energy sources to be connected to many energy consumers by pumping hot or cold water, and sometimes steam, as the energy carriers usually through insulated underground pipelines to meet demands for space conditioning, water heating and low temperature industrial heat. Centralised heat production can facilitate the use of low cost, and/or low grade, RE heat sources such as from geothermal, solar thermal, combustion of biomass including refuse-derived fuels and woody by-products that are not suitable for use in individual heating systems (Werner, 2004), and waste heat from CHP generation, industrial processes or biofuel production (Egeskog, Hansson et al. 2009).

This wide range of RE sources creates opportunities for district heating (DH) schemes to facilitate competition between various heating fuels and technologies (Gronheit and Mortensen 2003) by integrating a broad spectrum of fuels into a given scheme to enable switching between sources (see Swedish case study, Chapter 11). In many locations, individual heating systems in buildings using the direct use of natural gas, biomass boilers, electricity, heat pumps, solar thermal or geothermal systems (section 8.3.2) are strong competitors to DH (RHCAuthors? 2010) [TSU: Reference will need to be completed/corrected].

DH systems are most common in densely populated urban areas but can also be economically feasible in less densely populated areas, especially where an industrial low-to-medium grade heat load also exists (such as the kiln drying of timber). Historically, DH systems were mainly developed in countries with cold winters. After the oil crises in the 1970s, DH systems were developed in combination with (CHP) generation to reduce oil demand and increase overall energy system efficiency. As a result, several high latitude countries have a DH market penetration of 30-50% and in Iceland the share, using geothermal resources, reaches 96% (Fig. 8.14). World annual district heat deliveries have been estimated at 11 EJ but the data are uncertain (Werner 2004).

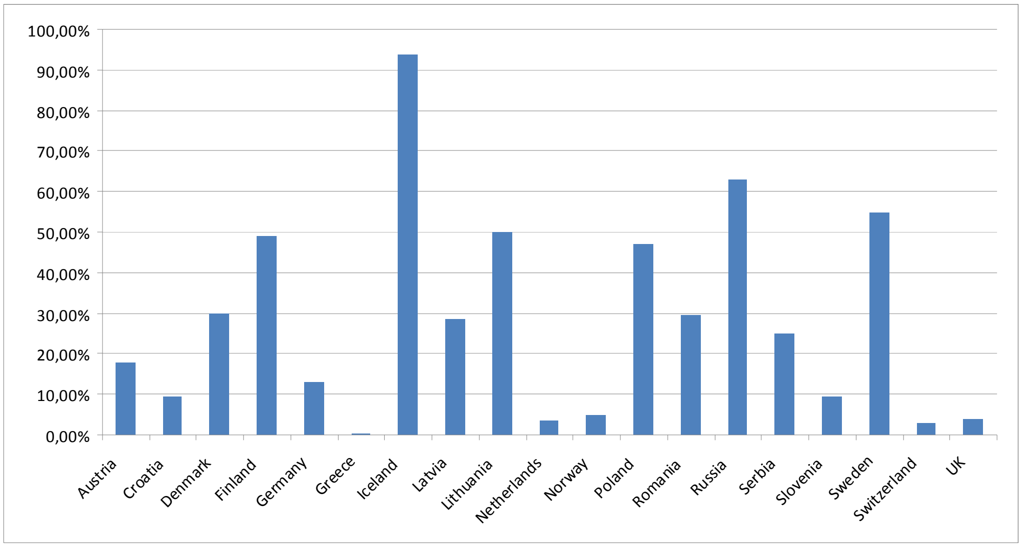


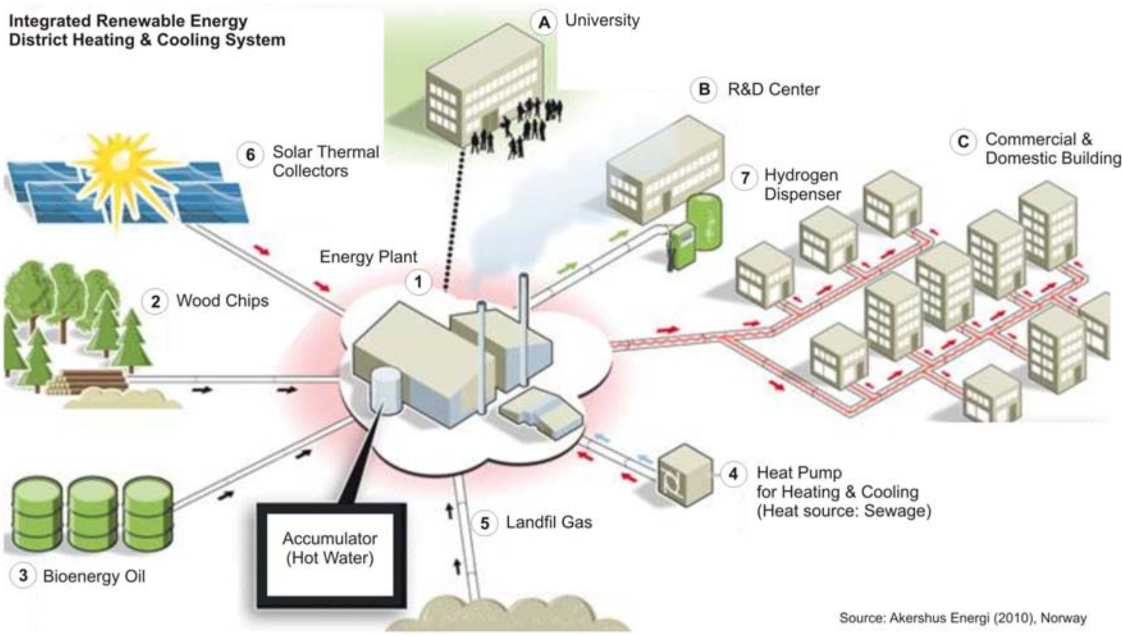
Figure 8.14: Share of district heating in total heat demand in selected countries (Euroheat&Power 2007).

DH is little used in lower latitude countries but district cooling is becoming increasingly popular in such regions, either through the distribution of chilled water or by using the DH network to deliver heat to run heat-driven absorption chillers. The Swedish town of Växjö, for example, uses excess heat from the biomass-fired CHP plant in summer for absorption cooling in one district, and a further 2MW chiller is planned (IEA, 2009b).

Combined production of heat, cold and electricity, as well as having the possibility for diurnal and seasonal storage of heat and cold, means that a high overall system energy efficiency can be obtained. However, the best mix of heat and cold sources together with the relevant technologies, depends strongly on local conditions, including demand patterns. As a result, the energy supply mix varies widely between different countries and systems (Euroheat & Power, 2006).
DHC systems can also provide electricity, through CHP system designs, and demand response options that facilitate increased integration of RE in power systems. This includes using electricity for heat pumps and electric boilers for DH with thermal storage used where excess electricity is generated (Lund et al., 2010). Using electricity for producing low grade heat may seem thermodynamically wasteful but other actions, such as spilling wind for example, can be even more wasteful.

8.2.2.2 Features and structure

Benefits of DH can occur on both the demand and supply sides (Fig. 8.15) through the use of geothermal, solar or biomass technologies and fuel flexibility. Occupiers of buildings connected to a DHC network can avoid operation and maintenance of individual heating equipment and rely on a professionally managed central system. An existing DHC network can be extended as appropriate to supply a larger number of customers and new low-carbon and RE sources can be integrated as they become available.



Source: Akershus Energi (2010), Norway

Figure 8.15: Integrated RE-based district heating and cooling system based on an actual installation in Lillestrøm, Norway, costing US$ 30 M [TSU: figure will need to be adjusted to 2005 US$] (Ulleberg 2010).

(1) Central energy system with 1,200 m^3 accumulator tank; (2) 20 MW_{th} wood burner system (with flue gas heat recovery); (3) 40 MW_{th} bio-oil burner; (4) 4.5 MW_{th} heat pump; (5) 1.5 MW_{th} landfill gas burner (5 km pipeline); (6) 10,000 m^2 solar thermal collector system (expected to be completed in 2012); (7) Demonstration of RE-based hydrogen production (water electrolysis and sorption enhanced steam methane reforming of landfill gas) for fuel cell vehicles (part of HyNor-project) to be completed in 2011.

Except in Iceland, the use of geothermal heat in DH schemes is small but the potential is great (Chapter 5). Also, enhanced geothermal systems (EGS) could be operated in CHP mode coupled with DH networks. The commercial exploitation of large heat flows is necessary to compensate for the high drilling costs of geothermal systems (Thorsteinsson and Tester 2010). In most cases, such a large heat demand is only available through DH networks, or to supply some industries (Hotson 1997).

Woody biomass, crop residues, pellets and solid organic wastes can be more efficiently used in a DH integrated CHP plant than in individual small-scale burners. Biomass fuels are important sources of district heat in several European countries particularly Sweden and Finland (Euroheat&Power 2007). The operation of a centralised biomass CHP plant with lower specific investment costs facilitates the application of cost-effective emission reduction measures also to reduce local air pollution.

In 2007, the more than 200 Mm^2 area of solar thermal collectors installed worldwide produced 146.8 GW_{th} but only a small fraction of that was for DH (Weiss, Bergmann et al. 2009). The costs of solar heating of water, space or a combination, might be reduced by shifting from small-scale, individual solar thermal systems to large-scale, solar heating plants. Higher solar shares can be achieved by using seasonal thermal storage systems, for which integration into a DH system with a sufficiently high heat demand is a prerequisite. Large central, solar thermal DH plants are found mainly in Germany, Sweden and Denmark.

An analysis of a future energy system in Denmark, based upon 100% RE by 2060, concluded that a gradual expansion of DH systems, and a switch to electric heat pumps for buildings that could not be connected to them, was the most efficient and least cost strategy for decarbonising space and domestic water heating (Lund, Möller et al. 2010).

8.2.2.3 Challenges associated with integration into heating/cooling networks

A DHC scheme involves a high up-front capital cost in piping networks. Distribution costs alone account for a significant share of total DH costs and are subject to large variations depending on heat density and the local conditions for building the insulated piping. Under Swedish conditions, DH, where available, can be competitive with alternative heating systems (Fig. 8.16).

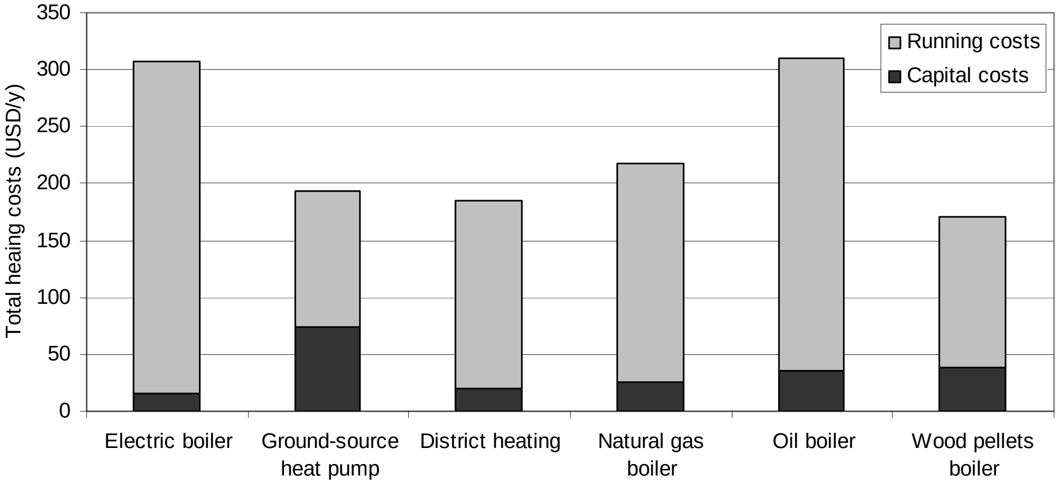


Figure 8.16: Average annual heating costs (US$2005 and including climate, energy and carbon taxes) for end-users in a typical 1000 m^2 multi-family building in Sweden using around 700 GJ/yr.

Notes: Capital costs are for end-user investment in the grid connection terminal, heat exchanger, boiler etc. Running costs are the payments to the utility. Date adapted from the Swedish Energy Markets Inspectorate (Ericsson 2009). See Chapter 11, case study for the fuel mix of Swedish DH systems.

Network capital costs and distribution losses per unit of heat delivered are lower in areas with high heat densities (expressed by kWh/m^2 or MW$_{peak}$ / km^2 or MWh/m of pipe length). Area heat densities can range from several hundred kWh/m^2 in dense urban, commercial and industrial areas down to below 20 kWh/m^2 in areas with dispersed single family houses. Corresponding heat distribution losses can range from less than 5% to more than 30%. The extent to which losses are considered a problem, however, depends on the heat source and cost.

Energy efficiency in buildings reduces the heat or cool demand and, as a result, total energy density is decreasing over time in some DHC systems. It can also flatten the load curve by reducing peak heating or cooling demand. Under some site specific conditions, investment costs for heat distribution networks could therefore become the predominant part of the total heating costs. Expected reductions in heat distribution costs through improved design and reduced losses suggest that the expansion of DH will remain economically feasible, even in areas with relatively low heat densities (Bruus and Halldor 2004). Improved designs include the co-insulation of smaller diameter forward and reverse flow distribution pipes.

8.2.2.3.1 Storage

Thermal storage systems can bridge the gap between variable, discontinuous and unsynchronised heat supply and demand. The capacity of thermal storage systems ranges from a few MJ up to several TJ; the storage time from hours to months; and the temperature from 20°C up to 1000°C.

These wide ranges are possible by using different storage materials (e.g. solid, water, oil, salt) and the corresponding thermal storage mechanisms.

In households with natural gas or electrical heating, hot water cylinder heat stores are commonly used. Solar systems can displace some or all of the energy demand, the gas or electricity becoming the back-up. For integrating large-scale, solar systems into DH networks, the development of systems for seasonal heat storage (Fig. 8.17) has made progress and several demonstration plants have been realised (Bauer, Marx et al. 2010). Heat and cold storage systems using latent heat of fusion or evaporation (phase change materials), or the heat of sorption, offer relatively high density storage (Bajnóczy, Palffy et al. 1999; Anant, Buddhi et al. 2008). Sorptive and thermo-chemical processes allow thermal storage for an almost unlimited period of time, since heat supply or removal occurs only when the two physical or chemical reaction partners are brought into contact. Both latent and sorptive heat storage technologies are in a relative early development phase.

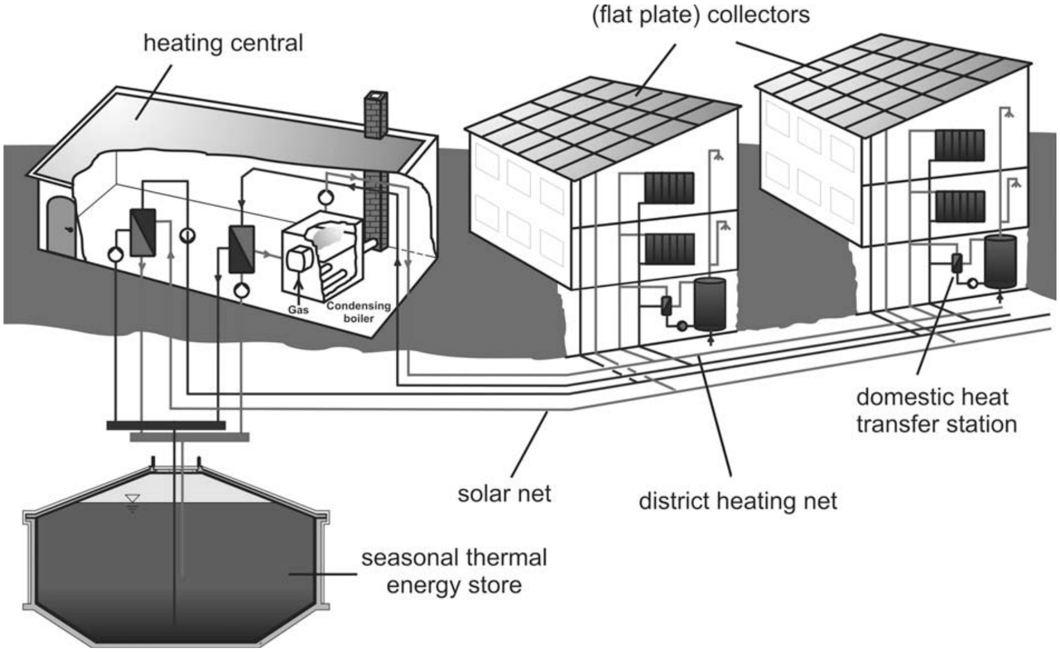


Figure 8.17: Central solar-supported heating plant with seasonal storage connected to a district heating system (Bodmann, Mangold et al. 2005)

The most suitable type of hot water storage system depends on the local geological and hydro-geological conditions, and the DHC system supply and demand characteristics. For short term storage (hours and days) the thermal capacity of the distribution system itself can be used for storage. Hot water storage in accumulator tanks is commonly used to even out hourly and diurnal variations in existing DHC systems. Longer term storage, often seasonal between winter and summer, is less common. In this case the main feature is having different types of geological storage, including duct storage systems and aquifer storage (Heidemann and Müller-Steinhagen 2006). With geological storage, relatively small temperature differences are employed. For example, heat may be injected during the summer to increase the temperature in an aquifer and then be extracted during the winter. Seasonal storage is likely to become more important with high shares of solar thermal energy in DHC systems.

8.2.2.3.1 Institutional aspects

DH schemes have typically been developed in situations where strong planning powers have existed, e.g., centrally planned economies, American university campuses, Western European countries with multi-utilities, and urban areas controlled by local municipalities.

Expanding the use of DHC systems would facilitate a higher share of RE sources such as deep geothermal and biomass CHP that require a large heat sink to be viable. Some countries are therefore supporting investments in DH as well as providing incentives for using RE. In Germany, for example, a market incentive programme supports new DH schemes through investment grants in existing settlement areas and for new development areas if the share of RE is above 50% (BMU 2009). In addition, the DH system operator receives a grant for each consumer connected to the new system. In Sweden, a high carbon tax has been a strong incentive to switch to RE heating options, biomass CHP in particular.

In the former centrally-planned economies, DH prices were regulated because of a social policy to sell heat below its market price. Today, in several countries with large DH schemes, an independent regulatory body ensures appropriate pricing where natural monopolies exist. In Denmark, for instance, a law that recognises the ownership of DH grids and the sale of heat as a monopoly, and hence regulates pricing and conditions of sale for the heat, has been a major factor in the development of the sector. A regulatory authority was established to oversee the formation of regulated prices and solve disputes between consumers and utilities (Euroheat&Power 2007).

In theory, third party access to DH networks could lead to a more competitive market for heating services, resulting in decreased heat prices and thus benefits for consumers. Markets for DH by nature are local, contrary to national and regional electricity and natural gas markets. If a new competitor invested in a more efficient and less expensive heat generation plant and could use the network of the existing DH utility, the incumbent utility may be unable to compete, the only choice then being to reduce the price or accept lost revenue. In this case, the stranded asset cost could be higher than the customer benefits obtained from having a new third party producer, resulting in a total net loss. More pronounced competition could be obtained if at least five producers operate in the same network. Most DH systems however are too small to host that many producers. Thus it remains debatable whether or not third party access in an existing DH system is financially sustainable and beneficial for the customer.

8.2.2.4 Options to facilitate integration into cooling networks

Cooling demands in buildings have grown recently because of increased internal heat loads from computers and other appliances, more rigorous personal comfort levels, and more glazed areas that increase the in-coming heat. The ratio of building surface to volume has also been rising but ingress of heat can be reduced by improved thermal insulation. Overall, modern building designs and uses have tended to increase the demand for cooling but reduced the demand for heating. This trend has been amplified by recent warmer summers in many areas that have increased the cooling demand to provide comfort, (particularly for those living in many low-latitude developing countries). Cooling load reductions can be achieved by the use of passive cooling options and active RE solutions. As for DH, the uptake of energy efficiency, deployment of other cooling technologies and structure of the market will determine the viability of developing a district cooling (DC) scheme.

Modern DC systems from 5 to 300 MW_{th} have been operating successfully for many years (in Paris, Amsterdam, Lisbon, Stockholm, Barcelona etc.). Where natural aquifers, waterways, the sea or deep lakes are utilised as the source of cold, then this can be classed as a form of RE source for cooling. Where a city or town is located near to a good water supply for the source of cold, then similar to DH systems, a network of pipes is used to carry the cold water from the supply to a series of buildings where it is passed through heat exchange systems. Sea water can be used but is more corrosive than cold, fresh water sources.

To use RE cooling most efficiently from a quality perspective, it is possible to set up a merit order of preferred cooling technologies from an economic point of view as below (IEA 2007), although the order may differ due to specific local conditions.

- Energy efficiency and conservation options in buildings and industry sectors, including white roofs and shading.
- Passive cooling options such as passive building design measures and summer night ventilation without the need for auxiliary energy.
- Passive cooling options using auxiliary energy, e.g. cooling towers, desiccant cooling, and aquifers.
- Solar-assisted, concentrating solar power, or shallow geothermal heat to drive active cooling systems.
- Biomass integrated systems to produce cold, possibly as tri-generation.
- Active compression cooling and refrigeration powered by renewable electricity.

Cooling demands located remotely from a cold water source could be met using complex, thermo-chemical sorption processes including chiller/heat pumps, absorption chillers, or compression chillers (IEA 2009). Such closed, active-cooling systems can be used for centralised or decentralised conditioning and involve a range of technologies to produce cooling driven by a RE source. Solar-assisted cooling (SAC) is promising with demonstration plants up to 3.6 MW_{th} (at Munich airport) but these technologies tend to be relatively costly at this early stage of their commercialisation, although the cost is declining with experience in system design (IEA 2007). One advantage of solar-assisted cooling technologies is that peak cooling demands often correlate with peak solar radiation and hence offset peak electricity loads for conventional air conditioners. Expansion of demand will depend, in part, on the other options available for cooling building space.

Ground source heat pumps (air-to-ground) can be used for space cooling virtually anywhere in the world in summer as well as for space heating (ground-to-air) in winter. Commercially available at small- to medium-scales (10-200 kW), they use the heat storage capacity of the ground as an earth-heat sink since the temperature at depths between 15 and 200 m remains fairly constant all year round at around 12 to 14°C. Vertical bores enable heat to be drawn out in the winter and concentrated within a building by a heat pump to reach the necessary temperature. The cost of drilling bores remains a high proportion of the total system cost so shallow horizontal pipes around 1-2 m depth can be an alternative, but less efficient system.

8.2.2.5 Benefits and costs of large scale penetration

The use of geothermal energy, solar energy or biomass in a DH or DC system provides heat at low or zero CO_2 emissions. The costs and benefits of a RE-based DH or DC system depends on site specific conditions such as the heat demand density or the availability of RE resources and appropriate infrastructure.

High penetration levels are not a technical problem for biomass or geothermal systems because of their high capacity factors. Many geothermal and biomass heating or CHP plants integrated into DH systems are successfully operating under commercial conditions. CHP as well as DHC developments often do not need financial incentives to compete in the market place, although government measures to address non-financial barriers, such as planning constraints, could aid greater deployment (IEA 2008).

Several large scale solar thermal systems with collector areas of around 10,000 m^2 were recently built in Denmark (Epp 2009). Under Danish conditions of high energy costs and carbon taxes, the integration of the solar collectors into existing DH systems will be redeemed in less than 10 years without any subsidies. At solar shares of up to 20%, the large number of customers connected to the DH system ensures a sufficiently large demand for hot water even in summer, so that high solar yields (~500 kWh/m²) can be achieved. Pilot plants with a solar share of more than 50% equipped with seasonal heat storage today demonstrate the technical feasibility of such systems (see the case study following).

8.2.2.6 Case studies

8.2.2.6.1 Solar assisted district heating system in Crailsheim, Germany

In Crailsheim, Germany, a new residential area with 260 houses, a school and sports hall has been designed to have more than 50% of the total heat demand covered by solar energy. A prerequisite for achieving such a high solar share is the use of a seasonal heat storage facility. The annual heat production of the system is 10.8 TJ, equivalent to the consumption of 300,000 litres of fuel oil.

Apartment blocks, new single houses and community buildings are equipped with solar collectors together with a 100 m³ buffer tank to directly cover instantaneous heat demand. A total annual heat demand of 4,100 MWh_{th} is expected to be met by the 7,300 m² solar collector area of which 700 m² are installed on a noise protection wall that separates the residential and commercial areas. Together with 75 boreholes at a depth of 55m and a second 480 m³ buffer tank, this provides seasonal storage. The integration of a 530 kW heat pump allows the discharge of the borehole storage system down to a temperature of 20°C, leading to reduced heat losses in the storage system and to higher efficiency of the solar collectors due to reduced return temperatures. It is expected that the borehole storage system will heat up to 65°C by the end of summer and the lowest temperature at the end of the winter heating period will be 20°C. Maximum temperatures during charging will be above 90°C. In a second phase, the heated residential area will be extended by 210 additional accommodation units requiring a total collector area around 10,000 m² and the seasonal storage system expanded to 160 boreholes (Mangold and Schmitt 2006). Solar heat costs in this advanced system are estimated to be around 0.24 US$/kWh[TSU: figure will need to be adjusted to 2005 US$] (Mangold, Riegger et al. 2007). By halving the fossil fuel consumption and by providing the remaining heat with a highly efficient fossil heating station linked to the existing DH network, emissions can be reduced by more than 1,000 t CO_2 /yr (Wagner 2009).

8.6.2.2.2 Biomass CHP district heating plant in Sweden

District heating in Sweden expanded rapidly between 1960 and 1985 having been entirely dependent on oil until the 1979 second oil crisis. Thereafter the fuel mix changed considerably and in 2007 biomass accounted for 44% of fuel supply in Swedish DH[8] (IEA 2009). Enköping is a documented and illustrative case of this transition that demonstrates an innovative approach integrating CHP, short rotation forestry and waste water treatment. The DH system was constructed in the early 1970s using oil-fired boilers until fuel switching started in 1979. After going through a period of using a mix of oil, solid biofuels, coal, electric boilers and LPG, the construction of a 45 MW_{th}, 24 MW_e biomass-fired CHP plant in 1994-1995 with the transition to near 100% biomass completed in 1998. This choice of fuel was driven by national CO_2 taxes, other policy instruments, and a local council decision to completely avoid fossil fuels (McKormick and Kåberger 2005).

Enköping differs from other DH systems due to a cooperation begun in 2000 between the local energy company, the sewage treatment plant and a local landowner. The energy company was

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[8] The remaining production was based on 35 PJ of municipal solid waste (18%), 20 PJ of industrial waste heat (10%), 10 PJ of coal (5%), 8 PJ TWh of oil (4%), 8 PJ of natural gas (4%), 10 PJ of peat (5%) and 20 PJ of heat from heat pumps (10%).

interested in diversifying fuel supply fearing that there may not be enough forest residue biomass in the region to meet future demand. The municipal sewage plant was obligated to reduce nitrogen discharges by 50%. The use of willow (*Salix*) was identified as a cost-effective approach to reduce nitrogen discharges by land treatment and at the same time produce biomass. An 80 ha willow vegetation filter was established in 2000 on nearby farmland. The farmer is paid for receiving wastewater and sewage sludge and for delivering biomass to the CHP plant at market prices. The success of this model is due to all parties being proactive and open to new solutions; advisors working as catalysts; regional and local authorities being positive and interested; and the risks being divided between the three parties (Börjesson and Berndes 2006). In 2008, the local area of willow plantations was increased to 860 ha and it is the ambition of the energy company to continue increasing the current 15% fuel share from *Salix*.

8.2.2.6.3 District heating in South Korea

Although most DHC schemes have been developed in Europe and North America, the Korea District Heating Corporation claims to be the world's largest DH provider (KDHC 2010) with heat production capacity from 11 plants exceeding 3.5 GW, including 1.5 GW of heat purchased from CHP plants operated by Korea Electric Power Corporation and from 85 MW of waste-to-energy incinerators owned by several municipal governments. The corporation has constructed over 1100 km of twin outward and return pipes as part of the Seoul metropolitan heating network. The corporation also aims to use biomass waste incineration facilities and solar heat to supply 30% of total heat energy to 10,000 new households by 2010.

It was established in 1985 as a government corporation for the purpose of promoting energy conservation and improving living standards through the efficient use of district energy. The state-run DH business aims to save energy as well as to promote the public benefits of DHC and its convenience. It provides DH to over 60% of the nation's total households with the aim to steadily expand the business and provide DHC services to 2 million households nationwide by 2015. Particular business emphasis is given to RE sources, including landfill gas.

8.2.2.6.4 District cooling systems

Few if any district cooling schemes have resulted from policy framing developments. Most have been commercial decisions made by the local municipality or building owners (IEA-SHC 2010). As a result of several successful demonstrations, the opportunity now exists for governments to encourage further deployment of RE cooling projects. Deep water cooling allows relatively high thermodynamic efficiency by utilizing water at a significantly lower heat rejection temperature than the ambient temperature. This temperature differential results in less electricity being consumed because a lower volume of cold water needs to be pumped. For many buildings, lake water is sufficiently cold that, at times, the refrigeration portion of the air-conditioning systems can be shut down and all the excess building interior heat transferred directly to the lake water heat sink. Power is needed to run pumps and fans to circulate the water and the building air but this is generally less than would be the electricity demand for refrigeration chilling to produce the same cooling effect.

Successful projects include 51 MW of cooling at Cornell University, Ithaca, USA, based on pumping around 20 m^3/min of 4°C water from the bottom of nearby Cayuga Lake through a heat exchanger before storing it in a 20,000 m^3 stratified thermal storage tank (Zogg, Roth et al. 2008). A separate water loop runs back 2 km before passing through the air-conditioning systems of the 75 campus buildings and Ithaca High School. In this US$(2005) 68 M scheme, the cooling water is discharged back to the lake at around 8-10°C and mixed by injection nozzles with the surface water to maintain stable water temperatures. The 1.6 m diameter intake pipe has a screen at 76m depth and this and the 38 discharge nozzles were carefully designed to minimise maintenance and environmental problems, having first closely monitored the ecology, hydro-dynamics, temperature strata and geophysics of the lake. Greenhouse gas emissions have been reduced significantly since the project started in 1999 compared with the original refrigeration based cooling system. This was due to both reducing the power demand for cooling by around 80-90% of the previous 25 GWh/yr and avoiding the 12-13t of CFCs that were used in the six chillers (Cornell 2005). There remain some concerns about bringing up phosphorus rich sediments from the bed of the lake and discharging them near to the surface, hence possibly encouraging algae growth.

Since 2004 Toronto has used cold water drawn from Lake Ontario 5 km away for a 207 MW cooling project of 3.2 Mm^2 of office floor area in the financial district. The lake water intake pipe at 86m depth runs 5 km out into the lake to ensure clean water is extracted since this is also the supply for the city's domestic water system. No warm water return discharge to the lake therefore results. Stockholm has a similar but smaller district cooling system based on extracting sea water from the harbour.

The Malaysian company Solar District Cooling Sdn Bhd (SDC) is planning to build its first solar district cooling plant having had experience of several solar absorption cooling projects for individual buildings (SDC 2010). The solar cooling technology will be located in Cyberjaya and used initially for office and residential applications. Although absorption chiller technology is reliable and becoming well understood, the typical payback time of more than 10 years has remained a deterrent to wider deployment to date. Policy support measures by interested governments could help bring down the manufacturing, project design and installation costs (IEA 2008).

8.2.3 Integration of renewable energy into gas grids

The main objective of a gas grid is to transport gaseous fuels from producers to consumers. A complete gas system consists of gas productions plants, transmission and distribution pipelines, gas storage, and gas dispenser/delivery systems for end-users. The design depends on the type and source of energy, the end-user demand, and locations of gas supply and demand.

8.2.3.1 Characteristics of RE with respect to integration into gas grids

Existing gas grids typically consists of different types of pipelines. High pressure transmission pipelines (40-70 bar) go between the production plant and the distribution network, passing over public land and third party properties, while distribution pipelines, including main feeders, station connections and valves, are usually contained on the property (generally owned by the customer) at the end-use point (EIGA 2004).

A gas transmission and distribution system is primarily designed to deliver adequate amounts of gas with a certain quality (e.g., heating value, pressure, and purity) to downstream users. The gas flow rate depends on the scale and physical attributes of the gas (such as molecular weight, viscosity, specific heat). The larger the pipeline diameter and the higher the pressure drop, the more gas volume that can be moved over a given distance (Mohitpour and Murray 2000). In the design of pipelines for high gas flow rates, there is an economic trade-off between increasing the diameter of the pipeline versus increasing the gas pressure. In order to balance supply and demand, gas storage also needs to be included at various levels in the system; the capacity depending on how the gas is produced, how the gas can be integrated into the gas grid and the end-use application. The size of gas storage is normally minimised to reduce costs and safety hazards.

The materials used in gas pipelines depend on the type of pipeline (transmission or distribution), location (sub-sea, over ground, underground), operating conditions (pressure, temperature, corrosion), and type and quality of gas to be sent through the pipeline. Metallic materials are mainly used in transmission pipelines or pipelines tolerant to higher pressures and temperatures, while plastics are used in distribution gas grids operating at lower temperatures (<100°C) and pressures (< 10 bar). Metal pipelines have the potential for internal and external corrosion problems (Castello, Tzimas et al. 2005).

Over the past 50 years large, integrated natural gas networks have been developed around the world. For example, the natural gas grid in the USA is a highly integrated transmission and distribution grid with more than 210 natural gas pipeline systems, 480,000 km of interstate and intrastate transmission pipelines, and 394 underground natural gas storage facilities (EIA 2007). European (EU27) natural gas has a total of 1.8 million km of pipelines and 127 gas storage facilities. The EU grid currently supplies more than 110 million customers, and is growing rapidly (Eurogas 2008).

Linking gas and electricity grids has been proposed by using surplus RE power to produce hydrogen by electrolysis and combining this, through the process of methanation, with CO_2 either from biogas, captured from fossil fuel combustion or extracted from the atmosphere, to produce methane as an energy store or carrier (Sterner 2009).

8.2.3.2 Features and structure of gas grids

Over the past decade there has been increasing interest in “greening” existing natural gas grids. In Europe the EU-directive 2003/55/EC opened up the gas grid to carry alternative gases such as hythane (a blend of hydrogen and natural gas), hydrogen, and biogas (Persson, Jönsson et al. 2006; NATURALHY 2009). In Germany the target for 2020 is to substitute 20% (by volume) of CNG (compressed natural gas used for transport) with biogas (1.12 PJ/year), while the target for 2030 is to substitute 10% of natural gas in all sectors with biogas (382 PJ/year) (Müller-Langer, Scholwin et al. 2009). Similar proposals have been made for the natural gas grid running along the West Coast of North America. In California a Bioenergy Action Plan has been introduced by the State Governor in an Executive Order on Biomass (CEC 2006).

Biogas can be upgraded to natural gas quality, blended with natural gas, and transported via existing or new gas grids. Until now most of the biogas produced around the world has been distributed in local gas systems primarily dedicated for heating purposes. In a few cases it has been transported via trucks to filling stations for gas-fuelled vehicles (Hagen, Polman et al. 2001; Persson, Jönsson et al. 2006). However, the biogas business is growing rapidly and is currently being commercialized by larger industrial players (Biogasmax 2009), and gas companies (e.g. National Grid, UK) that are now making plans on how to upgrade large quantities of biogas and inject this, at the required quality, into national/regional transmission gas pipelines (NationalGrid 2009) to offset some of the demand for natural gas in existing and future markets.

Synthetic gases, (syngas), a mixture of carbon monoxide, hydrogen, methane, higher hydrocarbon gases, and carbon dioxide, can be produced via gasification (partial oxidation) of coal, but also from biomass feedstocks (Chapter 2). Syngas derived from coal or solid organic waste is already widely used for cooking, heating, and power generation, especially in areas where natural gas is not available.

Once the energy feedstock for the biogas or syngas has been established, the end-use, heating, combined heat and power (CHP), raw material for chemical industry, or transport fuel, needs to be determined. The design of the gas clean-up, delivery and storage system will depend on the existing energy production and electricity system in the region where the gas grid is being considered. National and regional electricity and gas transmission grids can complement each other in the long-distance transport of energy. Similarly, local gas distribution grids could complement local heating and cooling networks (8.2.2).

Local gas distribution systems have traditionally used gas burning appliances to provide space and water heating. Using existing commercial internal combustion engine and micro-turbine technologies, biogas and syngas can also be used to fuel small to large CHP-systems. With the advent of commercial fuel cell technologies there are also new opportunities for small distributed, gas-based CHP-systems (DeValve and Olsommer 2006; Zabalza, Aranda et al. 2007).

Hydrogen can also be produced from RE sources. Future production and distribution will depend significantly on the interaction with existing electricity systems (Sherif, Barbir et al. 2005; Yang 2007). Over the next two to three decades, most of the pure hydrogen for fuel cell vehicle refuelling will probably be produced in distributed systems via small-scale, water electrolyzers or steam methane reformers (Riis, Sandrock et al. 2006; NRC 2008; Ogden and Yang 2009) and require local storage and distribution pipelines (Castello, Tzimas et al. 2005). In the long-term, large-scale production of hydrogen via water electrolysis using wind power, large-scale biogas-to-hydrogen reforming plants, and other technologies are conceivable (IEA 2006). Blending of hydrogen (up to 20%) with natural gas on a large scale and transporting the hythane mix long-distances in existing or new natural gas grids could be an option for a large-scale hydrogen economy (NATURALHY 2009), but the degree of pipeline leakage is uncertain.

8.2.3.3 Challenges caused by integration into gas grids

The economic and environmental viability of gas from local RE sources grids depends on reliability of supply and the energy infrastructure such as existing gas grids and electricity, heating and cooling networks. Having a clear policy for the end-use of the gas would avoid competition with other energy carriers.

The economic payback time to integrate biomethane into a gas grid depends on the location. If the installation is done at the end of a pipeline, as incremental capacity, the payback time can be relatively short. The community-scale biogas plant in Linköping Sweden is a good example of an economic and viable system since multiple organic wastes are treated and upgraded to biogas which is upgraded before distribution to a slow overnight filling station for buses, 12 public refuelling stations for cars, taxis and fleet vehicles, and for use in a converted diesel train with 600 km range (IEA 2010). The payback time is sensitive to the estimated long-term gas production and price that will be affected by taxation and carbon values as well as the future end-use demand of the gas. Local and regional differences in existing infrastructure (and energy supply and demand) make recommendations difficult for planning on a national and regional level.

Technical challenges relate to gas source, composition, and quality. The composition and heating value of biogas and syngas depends on the biomass source, gasification agent utilized in the process, and reactor pressure. The composition and parameters of fuel gases from different sources vary widely (Table 8.2). Commercial natural gas consists of 80-90% methane. Biogas from anaerobic digestion or landfill gas can be upgraded to reach similar methane composition standards as natural gas, for example, by stripping out the carbon dioxide content before being fed into the gas grids or used directly as fuel in combustions engines or fuel cells for stationary or mobile applications. Biomass derived syngas (produced from gasification followed by methanation) can consist of 83-97% methane along with 1-8% of hydrogen and hence has a similar heating value to commercial natural gas.

Table 8.2: Typical composition and parameters of gases from a range of sources including anaerobic digestion (AD) (Persson, Jönsson et al. 2006).

Parameter	Unit	Landfill Gas	Biogas from AD	North Sea Natural Gas	Dutch Natural Gas
Lower heating value	MJ/Nm^3	16	23	40	31-6
	kWh/Nm^3	4.4	6.5	11	8.8
	MJ/kg	12.3	20.2	47	38
Density	kg/Nm^3	1.3	1.2	0.84	0.8
Higher Wobbe index	MJ/Nm^3	18	27	55	43.7
Methane number		>130	>135	70	–
Methane	vol-%	45	63	87	81
Methane, variation	vol-%	35-65	53-70	–	–
Higher hydrocarbons	vol-%	0	0	12	3.5
Hydrogen	vol-%	0-3	0	0	–
Carbon oxide	vol-%	0	0	0	0
Carbon dioxide	vol-%	40	47	1.2	1
Carbon dioxide, variation	vol-%	15-50	30-37	–	–
Nitrogen	vol-%	15	0.2	0.3	14
Nitrogen variation	vol-%	5-40	–	–	–
Oxygen	vol-%	1	0	0	0
Oxygen, variation	ppm	0-5	–	–	–
Hydrogen sulphide	ppm	<100	<1000	1.5	–
Hydrogen sulphide,variation	ppm	0-100	0-10000	1-2	–
Ammonia	ppm	5	<100	0	–
Total chlorine(as Cl^-)	mg/Nm^3	20-200	0-5	0	–

Natural gas companies define the composition quality needed before accepting other gases into their distribution and storage system. This can create a market barrier for biogas and landfill gas producers, (more than for syngas) as only gases of a specified quality can be injected directly. Particulates and condensates need removal and there is low tolerance for other impurities.

- CO_2 can be removed by several methods but each with operational issues (Persson, Jönsson et al. 2006):
  - Absorption in water (water scrubbing) requires large amounts of water. Plugging of the equipment due to organic growth can also be a problem.
  - Absorption by organic solvents such as polyethylene glycols or alkanol amines require large amounts of energy for regenerating the solvent.
  - Pressure swing adsorption requires dry gas.
  - Separation membranes, dry (gas-gas) or wet (gas-liquid) require handling of the methane in the permeate stream (which increases with high methane flow rates in the gas stream).
- Cryogenic separation requires removal of water vapour and H_2S prior to liquefaction of the CO_2.
- Removal of corrosive H_2S from biogas is necessary to protect upstream metal pipelines, gas storage and end-use equipment. Micro-organisms can be used to reduce the level of H_2S in biogas by adding stoichiometric amounts of oxygen to the process (around 5% air to a digester or biofilter). Alternatively, simple vessels containing iron oxides can be used as they react with H_2S and can be easily regenerated when saturated.
- Siloxanes and organic silicon compounds, can form extremely abrasive deposits on pistons, cylinder heads and turbine sections and hence can cause damage to the internal components of an engine if not removed (Hagen, Polman et al. 2001; Persson, Jönsson et al. 2006).

Hydrogen needs purifying and drying before it is stored and distributed. For use in low temperature fuel cells it normally has to be high purity (> 99.9995% H_2 and <1 ppm CO). Industrial hydrogen with lower purity can be transported in dedicated transmission and distribution pipelines so long as there is no risk of water vapour building up, or any other substances that can lead to internal corrosion. Regular checking for corrosion and material embrittlement in pipelines, seals, and storage equipment is also important (EIGA 2004).

8.2.3.4 Options to facilitate the integration into gas grids

8.2.3.4.1 Technical options

The two main technical challenges when integrating RE-based gases into existing gas systems are pipeline compatibility and gas storage.

RE-based gas systems are likely to require large gas storage capacity to account for variability and seasonality of supply. Since RE-based gases can be produced regionally and locally, storage is most likely to be located close to the demand of the end-user. The size and shape of storage facilities will depend on the primary energy source and the end-use. In small applications, the pipelined can also be used for gas storage (Gardiner, Pilbrow et al. 2008). In case where there are several complimentary end-users for the gas, infrastructure and storage costs can be shared. Hydrogen can be injected into existing natural gas grids, but this may first require some upgrading of the existing pipelines and components (Mohitpour and Murray 2000; Huttenrauch and Muller-Syring 2006). Pure hydrogen has a lower volumetric density compared to natural gas so pipelines will need higher pressures or around 3 times larger diameter (in order to carry the same amount of energy per unit time as existing natural gas pipelines.

Dedicated distribution gas pipelines for RE-derived gas (biomethane, hydrogen, syngas, or gas mixture) can operate at low pressures and volume flow rates (but needing increased diameter to give similar energy delivery). This opens up the opportunity for simpler designs where gas with a lower volumetric energy density can be distributed locally in polymer pipelines made of less costly materials. The required gas quality could be less stringent than if injected into other gas pipelines but would be governed by the specifications for end-use applications.

After a RE gas has been upgraded, purified, dried, brought up to the prescribed gas quality, and safely injected into a distribution grid, the main operational challenge is to avoid leaks and regulate the pressure and flow rate so that it complies with the given pipeline specifications. Compressors, safety pressure relief systems, and gas buffer storage need to be available continuously in order to maintain the optimum pressures and flow rates in the grid.

Options for large-scale storage of biomethane are similar to those of natural gas, namely compressed (CNG) or liquefied (LNG). Small to medium-sized gas storage buffers tanks can be introduced into distribution systems to balance local supply and demand. Methane can be collected and stored for a few days in inflatable rubber or vinyl bags. In large, industrialized biogas process plants, upgraded gas is normally stored at high pressures in steel storage cylinders (as used for LPG), depending on the size of the production plant and mode of further distribution (truck versus pipeline). Ideally, a compressed biogas dispensing station for vehicles should be connected to a local biogas source and/or to a gas pipeline. Distribution of compressed biogas cylinders can be achieved using trucks as liquefaction before transport in tankers (as used for LNG) would likely add significant cost and complexity.

For RE-based hydrogen over the next few decades the general consensus is that it will mainly be produced in smaller distributed systems (Riis, Sandrock et al. 2006). For example, water electrolysers or small-scale steam methane reformers only require small to medium sized hydrogen storage whilst if in the long-term hydrogen is derived from large, integrated RE-systems, then larger hydrogen storage units might be needed. Small-scale storage of hydrogen can be achieved in steel cylinders around 50 l and at 200 bar. Composite-based hydrogen gas cylinders that can withstand pressures up to 700 bar have been developed and demonstrated in hydrogen vehicle-fuelling stations. Hydrogen can also be stored at low pressures in stationary metal hydrides, but these are relatively costly and can only be justified for small volumes of hydrogen or if compact storage is needed. In integrated gas grids, it is probably more suitable to use low-pressure (12-16 bar) spherical containers that can store relatively large amounts (>30,000 m^3) of hydrogen (or methane) above ground (Sherif, Barbir et al. 2005). For safety reasons, such storage will normally have to be situated far away from densely populated areas, and hence would require a longer gas pipeline to the end-user.

At the large-scale, hydrogen can be stored as a compressed gas or cryogenically in liquid form, but this would cost more than biomethane storage due to the lower volumetric density and boiling temperature (-253ºC). In practice, about 15-20% of the energy content in the hydrogen would be required to compress it from atmospheric pressure to 200-350 bar. Around 30-40% of total energy is required to store liquid cryogenic hydrogen (Riis, Sandrock et al. 2006). Natural underground options such as caverns or aquifers for large-scale, seasonal storage can be found in various parts of the world, but their viability and safety must be evaluated on a case-by-case basis.

8.2.3.4.2 Institutional options

The main institutional challenges related to integrating RE-based gas into existing gas systems are adequacy of supply, security, safety, and standards (McCarthy, Ogden et al. 2006). Adequacy of supply can be influenced by the variability and seasonality of the RE resource. For example, biomass resources can be seasonal and quantities can vary from year to year. If hydrogen is produced from a variable RE source, the fluctuations of the supply must be considered. Designing a system to provide gas on demand may require storage of the primary feedstock (e.g. baled straw, or pelletized biomass) or storage of the hydrogen energy carrier. Capacity of the gas transmission and distribution system also needs to be able to meet demand for the gas.

The security of a gas pipeline system involves assuring a secure primary supply and building robust networks that can withstand either natural or malicious physical events. Networks that carry several gases are likely to be more secure than a network wholly dependent on a single feedstock. Similarly, diverse local or regional RE resources used for gas production can offer more secure supply than a single source of imported natural gas. In order to enhance network security, gas pipeline networks often include some degree of duplication (such as having multiple pathways between supplier and user) so that a pipeline disruption in a single network cannot shut down the entire system. Assessing vulnerability to malicious attacks for an extensive pipeline system over thousands of kilometres is a daunting task, and may require technological solutions such as intelligent sensors that report back pipeline conditions via GPS technology to allow rapid location of a problem and corrective action.

Hydrogen is widely used in the chemical and petroleum refining industries and safety procedures and regulations for that application are already in place. Industrial hydrogen pipeline standards and regulations for on-road transport of liquid and compressed hydrogen have been established. However, there is a lack of safety information on hydrogen components and systems, which poses a challenge to the commercialization of hydrogen energy technologies. Codes and standards necessary to standardize technologies and gain the confidence of local, regional and national officials involved with planning the increased use of hydrogen and fuel cells, are being focused on developing safety and operational standards for hydrogen systems, both nationally (e.g. US DoE National Hydrogen Association (NHA); US Fuel Cell Council; Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW), Germany) and internationally (e.g. New Energy and Industrial Technology Development Organization (NEDO), Japan; the International Partnership for

Hydrogen Energy (IPHE); and the International Energy Agency's Hydrogen Implementing Agreement (HIA)).

Feed-in regulations can enable the introduction of biomethane into a natural gas grid in a similar way to RE power generation feeding into an electricity grid. There is no one single international gas standard for pipeline quality of biogas or hydrogen, although countries such as Sweden and Germany have developed their own national standards (Persson, Jönsson et al. 2006) (Table 8.3).

Table 8.3: National standards for biomethane injection into natural gas grids for Sweden and Germany (Persson, Jönsson et al. 2006).

Parameter	Unit	Demand in Standard
Sweden		
Lower Wobbe index	MJ/Nm^3	43.9 – 47.3 (i.e. 95-99% methane)
MON (motor octane number)	–	> 130 (calculated according to ISO 15403)
Water dew point	°C	$< T_{ambient} - 5$
$CO_2 + O_2 + N_2$	vol %	< 5
O_2	vol %	< 1
Total sulphur	mg/Nm^3	<23
NH_2	mg/Nm^3	20
Germany		
Higher Wobbe index	MJ/Nm^3	46.1 – 56.5 (> 97.5% HHV methane)
	MJ/Nm^3	37.8 – 46.8 (i.e.87-98.5% LHV methane)
Relative density	–	0.55 – 0.75
Dust	–	Technically free
Water dew point	°C	$< T_{ground}$
CO_2	vol %	< 6
O_2	vol %	< 3 (in dry distribution grids)
S	mg/Nm^3	< 30

8.2.3.5 Benefits and costs of large scale penetration of RE into gas grids

Benefits and costs can be assessed using both economic (capital expenditure, operation and maintenance costs etc.) and environmental (GHG emissions, local air pollution, energy input ratio, air pollution etc.) indicators. The relevant parameters are significantly affected by the type of RE gas source, the design of gas production, storage, and distribution systems, and the end-use applications (transport or stationary). Comparisons between various alternative transport fuels are discussed in Section 8.3.1). This section focuses on the benefits and costs related to the integration of RE into gas grids.

A clear benefit from expanding the use of RE-based gas, particularly methane, is its compatibility with existing gas infrastructure. The costs of transmission and distribution of biomethane would be similar to that of existing gas systems giving a straightforward transition path for integration into existing supply chains and gas grids. Biomethane is already well-established for heating, cooking, power generation, CHP and transport applications. More than 9 million CNG (and LNG) vehicles already operate worldwide (Åhman 2010) whereas the market for hydrogen-fuelled vehicles is limited to utility vehicles such as forklift trucks and demonstration cars and buses.

GHG emissions related to producing and upgrading a RE-based gas should be assessed before a system is implemented. Methane leakages to the atmosphere during the gas up-grading, storage and distribution process and from heat and power consumed during up-grading and compacting will affect the overall energy efficiency and GHG emissions (Fig. 8.18) (Pehnt, Paar et al. 2009). Other studies have shown that vehicles fuelled by landfill gas can reduce CO_2 emissions by around 75% compared to using CNG, or even higher if using biogas produced from manure (NSCA 2006). The general conclusion is that all the waste and residue resources should be utilized so that GHG-emissions are minimized.

To compete with other energy carriers, the cost of producing and up-grading biogas to the quality required for injection into an existing gas grid should be minimised. It depends on the choice of technology (e.g., for CO_2 removal; 8.2.3.3). A comprehensive study of several biogas plants in Sweden showed that the electricity consumed to upgrade biogas is about 3-6 % of the energy content of the cleaned gas, and the cost to upgrade biogas is about US$(2005) ~0.05-0.20 /MJ (Persson 2003).

The cost per unit of energy delivered using a gas pipeline is dependent on economies of scale and gas flow rate. The major cost is the pipe itself plus costs for installation, permits and rights of way. The cost of a local distribution pipeline depends mainly on the density of the urban demand with more compact systems yielding a lower cost per unit of energy delivered. When designing a new gas grid, planning for anticipated future expansions is recommended as adding new pipes can be a costly option. If demand grows rapidly, increasing the pressure to provide additional gas flow may be cheaper than adding new pipelines. Biomethane distribution and dispensing at the medium scale (assuming a mix of pipelines and via cryogenic bottles by truck with an average cost of US$(2005) ~7.6 /GJ) is US$(2005) ~6.4–15.3 /GJ (Fig. 8.19) which is substantially higher, than for liquid fuels at US$(2005) ~2.5-3.8 /GJ) (Åhman 2010).

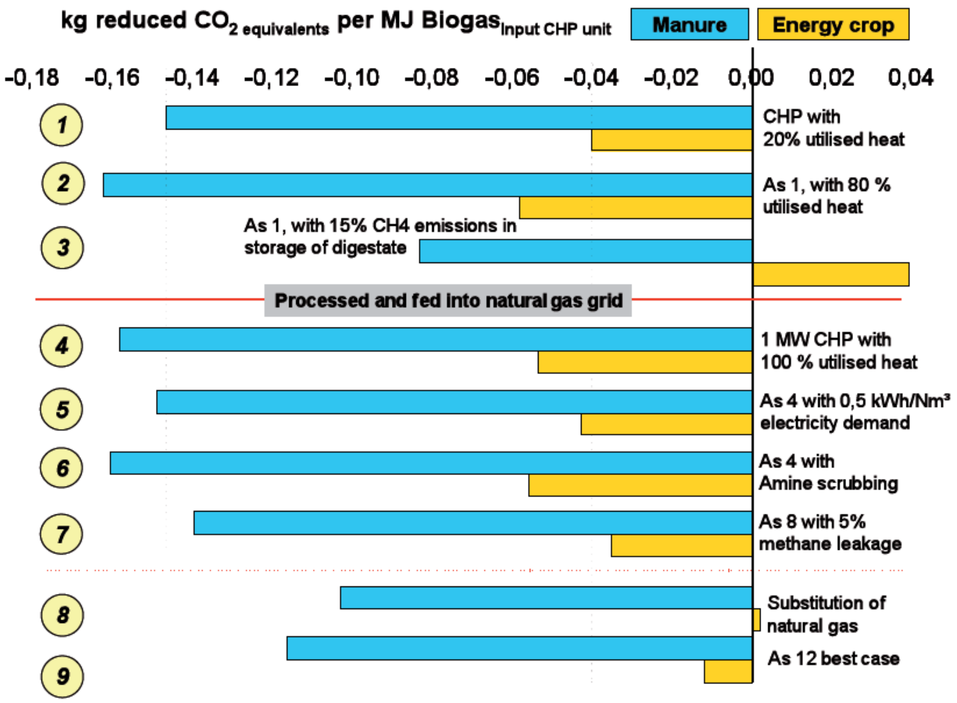

Figure 8.18: Potential reduction of greenhouse gas emissions by a biogas reference plant (kg $CO_{2\,eq}$ /MJ biogas input compared with the use of natural gas for several gas supply systems producing 500 kW_e from animal manures as feedstocks (blue) or corn silage (orange) (Pehnt, Paar et al. 2009). Note: Assumptions used found in more detailed study (Pehnt, Paar et al. 2009)

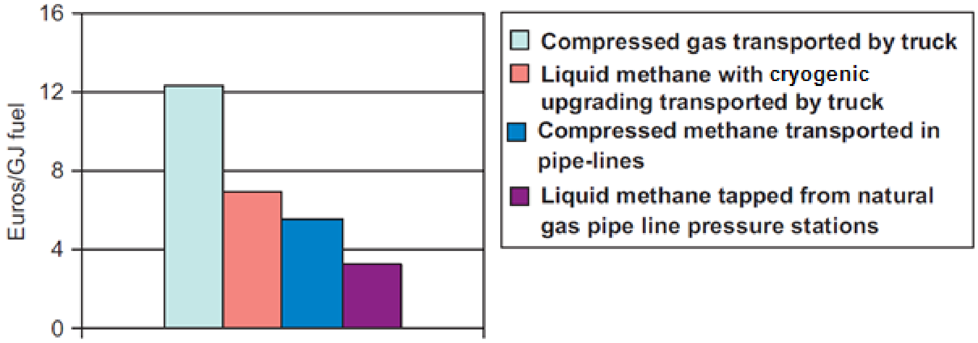

Figure 8.19: Cost for distribution and dispensing of biomethane at medium scale (Åhman 2010). Note: Cost data from 2006 when 1 EUR(2006) = 1.27 US$(2005).

In order to blend RE-derived gases into the gas grid, the gas source needs to be located near the existing system to avoid high delivery costs. For remote plants using the methane or hydrogen on-site would avoid the need for gas distribution. Blending syngas or hydrogen into the natural gas system could be feasible, but may require changes to gas distribution and end-use equipment designed for natural gas. “Town gas” city networks that currently employ fossil fuel-derived syngas may be good markets for biomass-derived syngas.

Potential for hydrogen production from RE resources is greater than for biogas or biomass-derived syngas. Limiting factors are likely to be capital costs and time involved in building a new hydrogen infrastructure. Hydrogen used as a transport fuel would require several hundred billion dollars invested over four decades to fully develop a suitable infrastructure for refuelling vehicles (NRC 2008). Incorporating variable RE sources could add to the cost because of the added need for storage.

The outlook for RE-derived gaseous energy carriers depends on how quickly they can penetrate the energy system and how much can they ultimately contribute. In Europe, biomethane could potentially replace 17.5 EJ of imported natural gas in 2020 (Fig. 8.20) (Müller-Langer, Scholwin et al. 2009) but depending on competition for the available biomass resource[9] (Eurogas 2008).

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[9] By way of comparison, total natural gas consumption in Europe (EU27) in 2007 was about 19.7 EJ, being 24% of total energy needs.

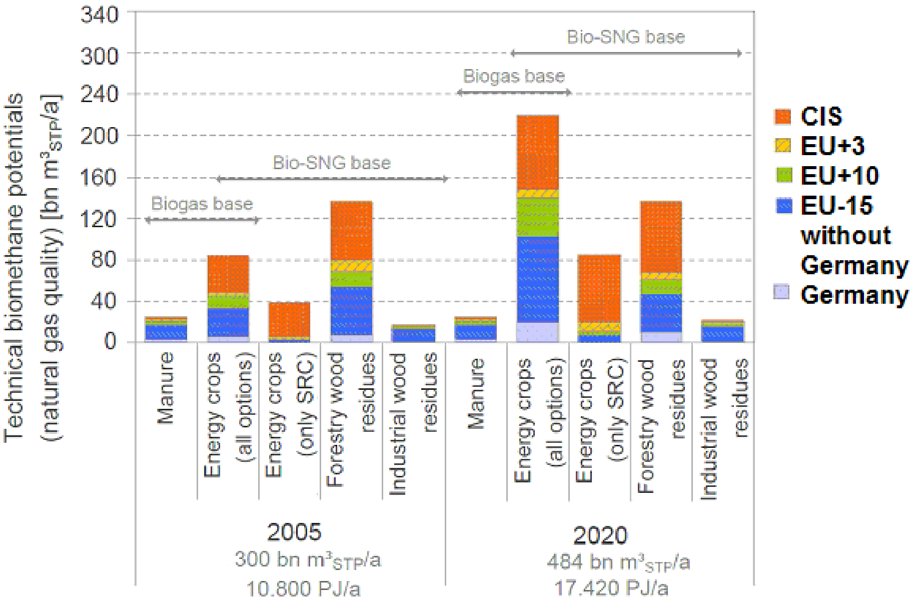

Figure 8.20: Technical potentials of biomethane at standard temperature and pressure (STP) in the EU-region in 2005 and 2020 (Müller-Langer, Scholwin et al. 2009).

8.2.4 Liquid fuels

8.2.4.1 Characteristics of RE with respect to integration

Renewable liquid fuels are basically produced from biomass sources (Chapter 2) or via solar fuels (Chapter 3). Currently most biofuels are produced from sugar, carbohydrate and vegetable oil food crops. Alcohol fuels can be used in blends typically up to 10% (in volumetric terms) with gasoline in regular spark ignition engines or blended in any proportion with gasoline for use in *flex-fuel* vehicles (Section 8.3.1). Biodiesel can be used in compression ignition engines either neat or blended with mineral diesel, though blends above 5% are not always covered by engine manufacturer warranties. Biogas methane, if it meets appropriate specifications, can also be combusted directly in spark-ignition internal combustion engines similar to those suitable for running on compressed natural gas (CNG). Solid ligno-cellulosic biomass sources can be converted to “second generation” liquid fuels by means of biochemical processes such as enzymatic hydrolysis or by thermo-chemical processes to produce synthesis gas (mainly CO + H_2) followed by the established Fischer-Tropsch conversion to produce a range of synthetic liquid fuels suitable for aviation, marine and other applications (Sims, Taylor et al. 2008).

The demand for large amounts of traditional solid biomass primarily in developing countries for cooking and heating could be replaced by more convenient fuels such as LPG but others produced from biomass such as ethanol liquid or gels (Utria 2004; Rajvanshi, Patil et al. 2007) or dimethyl ether (DME) (IEA 2008). Most of the projected demand for liquid biofuels, however, is for transport, though industrial demand for bio-lubricants and chemicals, such as methanol, for use in chemical industries could increase.

Liquid biofuels integrated into existing transport fuel systems can make use of existing infrastructure to transport and distribute oil products. Transition barriers would be relatively low as the biofuels could be introduced without costly modifications to existing petroleum storage and delivery systems, and can take advantage of existing infrastructure components already used (NAS 2009). Some related costs could eventuate for blending and for additional technical adaptations of fuel storage tanks, fuel pumps, or provision of new installations. The type of fuel storage and delivery system will vary depending on the properties of the biofuel and compatibility with the existing petroleum-based fuel system. Most common biofuels have fairly similar properties to gasoline and diesel so can be blended reasonably easily with these petroleum fuels, but cold weather conditions can represent difficulties, also for storage and transport, especially for some biodiesels which may form gels and stop flowing. At high levels of biofuel use, various transport and delivery modes from refinery to terminal might be used. Fuels could be transported from bio-refineries (Chapter 2) via truck, barge, tanker and/or pipeline to terminals and from there trucked to retail outlets. Storage and distribution costs would be similar for petroleum-based fuels. Bio-refineries are generally much smaller in capacity than oil refineries and could be widely located in geographic regions where the resource exists. In the United States for example bio-refineries are situated in the Mid-west or South-east whereas oil refineries are concentrated along the coasts.

Integration issues are particularly challenging for biofuels. Although the cost of delivery is a small fraction of the overall cost, the logistics and capital requirements for widespread expansion could present many hurdles if they are not well planned. Ethanol and gasoline blends (gasohol) cannot be easily stored, transported and delivered in the existing petroleum infrastructure because of the incompatibility of materials and water absorption by anhydrous ethanol in the pipelines. However, in Brazil alcohol produced from sugar cane has been successfully transported in the same pipelines used for oil products over the last 20 years. In addition, ethanol has only around two-thirds the volumetric energy density of gasoline, so larger storage systems, more rail cars or vessels, and larger capacity pipelines would be needed to store and transport the same amount of energy. This would increase the fuel storage and delivery cost.

The possibility exists to use some by-products of biofuel production as raw materials for electricity generation or biogas production. Electricity generation can be an integral part of biofuel production, for example from the sugarcane residue, bagasse. Integration with the existing electricity grid system is being successfully achieved in Brazil and elsewhere in cogeneration schemes (Chapter 2) after the energy demand of the processing plant has been met (Rodrigues, Faaij et al. 2003; Pacca and Moreira 2009). Since the sugar cane harvest period coincides with the dry season in Brazil, the greater availability of bioelectricity complements the country’s hydroelectric system. Biogas production under current production methods for bioethanol and biodiesel, uses the by-products generated by these methods. Thus, biogas production systems also have the potential to be integrated in various existing bio-refinery models. The biogas could either be used for electricity generation as a vehicle fuel (Börjesson and Mattiasson 2008), or fed into gas grids.

8.2.4.2 Features and structure of liquid fuel supply systems

Ethanol is widely used today as a transport fuel additive or blend especially in USA, Japan, France and Brazil or as a neat fuel (Brazil, Sweden). The structure of a biomass-to-liquid fuel system for 1st generation biofuels is well understood (Fig. 8.21).

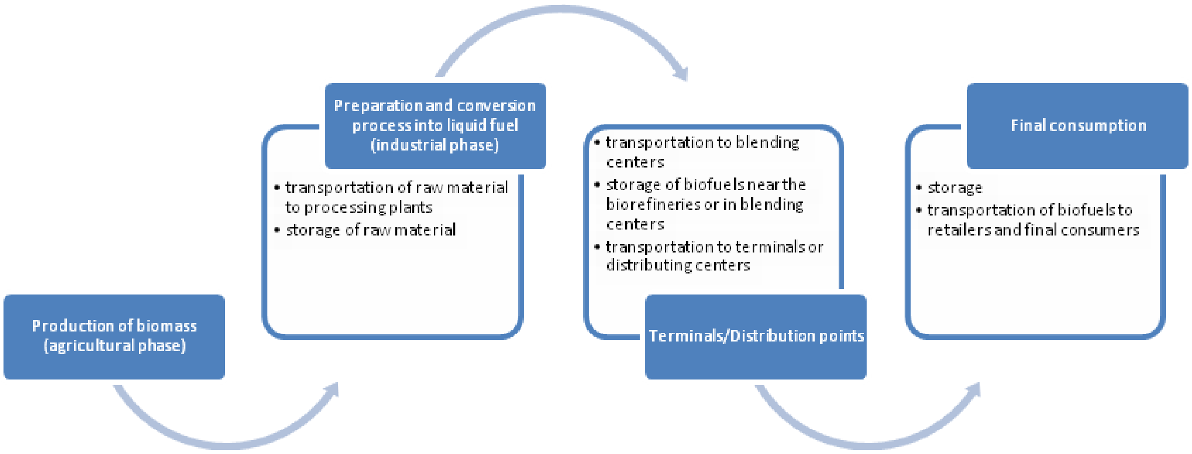

Figure 8.21: A typical biofuel production, blending and distribution system.

Transport of bulky, low energy density biomass feedstocks (sugar cane, corn grain, palm kernels, straw etc.) to a biorefinery by road or rail can be costly and produce some GHGs. Storage costs to provide all-year round supply as far as is feasible also play a critical role in the development of the industry (NAS 2009).

Ethanol and biodiesel can be transported by road tanker, rail, ship or pipeline (when production is geographically concentrated) (NAS 2009) and blended with gasoline or diesel respectively at refineries, production sites, or special blend centres during the distribution of fuels to vehicle service stations. For longer distances rail transport can be a more efficient and cost effective delivery mode than road but is not always available (Reynolds 2000). Biofuels and blends can be stored at their production sites, alongside oil refineries or storage tank facilities and at service stations in underground tanks. Similar care needs to be taken regarding safety and environmental protection, as for petroleum products. Due to the agricultural seasonality of crops grown specifically as feedstocks, storage of the biofuel produced is crucial to meet all-year-round demand. Biodiesel tends to be more prone to variation in composition during storage due to the action of micro-organisms leading to rises in acidity and corrosion than ethanol which is more biologically stable.

8.2.4.3 Challenges of integration

Decentralized biomass production, seasonality and remote agricultural locations not necessarily near existing oil refineries or fuel distribution centres can impact on the logistics and storage of biofuels.

Sharing oil-product infrastructure (storage tanks, pipelines, trucks) with biofuels, especially ethanol, can give problems of water contamination and corrosion, requiring new materials needed to preserve the lifetime of the equipment. Moisture from condensation in oil-product pipelines can increase the water content of the ethanol being transported and if it exceeds the technical specification for the biofuel, further distillation will be required. Ethanol can dissolve and carry any impurities present inside multi-product pipeline systems that are potentially harmful to internal combustion engines. Ethanol’s affinity for water and its solvent properties may require use of a dedicated pipeline or improved clean-up procedures between products sent through multi-product pipelines. Moisture absorption and phase separation during pipeline shipment can be avoided by first shipping hydrous ethanol, which is then used directly by end-users or distilled, followed by anhydrous ethanol for direct blending with gasoline. An alternative strategy is sending a “sacrificial buffer" of neat (100%) ethanol down a pipeline to absorb any moisture ahead of sending the primary batches of ethanol or blends. The buffer shot is discarded or re-distilled.

Ethanol in high concentrations can lead to accelerated stress corrosion cracking (SCC) in steel pipelines and storage tanks, especially at weld joints and bends. This can be avoided by adding tank liners, using selective post-weld heat treatments, and coating of internal critical zones (at pipeline weld points, for example) but these all increase system costs. Ethanol may degrade certain elastomers and polymers found in seals and valves in pipelines and terminals as well as some engines so these may need replacement. New pipelines could be constructed with ethanol-compatible polymers in valves, gaskets, and seals and be designed to minimize SCC (NAS 2009).

8.2.4.4 Options to facilitate integration

8.2.4.4.1 Technical options

Technologies will continue to evolve to produce biofuels that are more compatible with the existing petroleum infrastructure (Sims, Taylor et al. 2008). In some countries, the revision of liquid transport fuel standards to enable biofuels to be incorporated whilst assuring the integrity of the existing fuel distribution system, has been a slow process. This can inhibit the integration of biofuels into the supply system. Quality control procedures also need to be implemented to ensure that biofuels meet all applicable product specifications (Hoekman 2009) and facilitate integration. International trade in biofuels instigated a need for international standards to be developed. Blending of biofuels needs to account for regional differences in the predominant age and type of vehicle engines and local emission regulations. Variations exist in the current standards for regulating the quality of biodiesel reaching the market due to the different oil and fat feedstocks available, though less so for ethanol since it is a single chemical compound. This translates to variations in the performance characteristics of each biofuel.

A comparison was made of existing biofuel standards in U.S., Brazil and the EU) (Task Force, 2007). The standards for biodiesel in Brazil and US reflect its use as a blending component in conventional mineral diesel fuel, whereas the European standard allows for its use as a blend or neat fuel. Bioethanol technical specifications differ with respect to the water content but do not constitute an impediment to international trade (NIST 2007).

8.2.4.4.2 Institutional aspects

Agencies in charge of regulating oil-product markets could also include biofuels under their jurisdiction. These agencies are appropriate institutions to deal with issues such as security of biofuel supplies, safety and technical specifications (or standards) and quality control at both the production and retail levels. This is currently the case for Brazil where the regulator for the oil sector also regulates biofuels.

8.2.4.5 Benefits & costs of large scale penetration

Existing transport, storage and dispensing equipment at vehicle refuelling stations can be modified to handle biofuels and blends as has been successfully achieved in the US, Brazil, Germany and elsewhere. Underground storage-tank systems, pumps, and dispensers need to be converted to be compatible with higher biofuel blends and to meet safety requirements. Issues relating to the retrofitting of existing facilities are similar to those associated with pipeline transport (8.2.4.3) including phase separation, SCC, and the degradation of incompatible materials (NAS 2009).

Ethanol terminals usually have one or more storage tanks ranging from 750 to 15,000 m^3capacity. New ethanol storage tanks cost around US$ 170 /m^3 capacity for small tanks to US$ 60/m^3 for large tanks [TSU: figures will need to be adjusted to 2005 US$/$m^3$] (Reynolds 2000). It may be possible to refurbish gasoline tanks for ethanol storage at lower costs. Collection terminals at ports and refineries often include equipment for blending ethanol, receiving shipments via rail, truck, boat or pipeline, and loading blended product on to road tankers (Reynolds 2000).

In the US, most ethanol is transported by rail, road tanker and barge (NCEP 2007), but since 2008 batches have been sent through gasoline pipelines in Florida (KinderMorgan 2010). Capacities and costs vary for ethanol storage and delivery equipment (Table 8.4). As a point of reference, ethanol plants in the US produce 300-1200 m^3/day; demand for 1 million cars using E10 would be about 400- 800 m^3/ day; and storage facilities can hold 4000-12,000 m^3.

Table 8.4: Equipment capacity for ethanol storage and long-distance transport (RFA 2009).

	Capacity	**Cost (US$ 2005)**	**References**
Truck/trailer	25 m^3	\$103,000 \$141,000	(USEPA 2007) (Reynolds 2000)
Rail car	90 m^3	\$85,000	(USEPA 2007)
River barge	Several units at 1200 m^3/unit	\$5M for one 1,200 m^3unit	(USEPA 2007)
Ocean ship	3000-30,000 m^3		(Reynolds 2000)
Pipeline (300 mm diameter)	12,000 m^3/day	\$0.34-0.85 M/km	
New terminal storage tank	3000 m^3 6000 m^3	\$510,000 \$860,000	(Reynolds 2000) (Reynolds 2000)
Retrofit gasoline storage tank	1200 m^3	\$18,800	(USEPA 2007)
Blending equipment		\$170,000-450,000	(Reynolds 2000)
Total terminal refit	6,000 m^3 capacity	\$1.13 M	(Reynolds 2000)
Ethanol production plant	230-950 m^3/day		
Ethanol terminal	600 m^3 (local) 12,000 m^3 (regional)		

Tankers are often used to distribute ethanol from large regional terminals served by boat, barge or rail, to smaller local terminals that have insufficient storage to receive barge or rail deliveries.

Rail shipment is generally the most cost effective delivery system for medium and longer distance (500 to 3,000 km) to destinations without port facilities (Reynolds 2000). Because of the number of units and smaller unit volumes compared to barges, as well as the more labour intensive efforts for cargo loading, unloading and inspection, rail shipments require more input at the terminal. Unit trains for ethanol (containing up to 75 railcars) have been proposed as an alternative to pipeline development (Reynolds 2000).

Barges are used for long distance transport when biofuel production plants have access to rivers or sea. In the US for example, barges travel down the Mississippi river from Midwestern ethanol plants to ports at the Gulf of Mexico where the ethanol is stored before being transferred to ships for transport to overseas or national coastal destination terminals for blending.

Storage and transport costs are a relatively small portion of total costs. The costs of transporting large ethanol volumes over long distances for waterway (barge and ship) and rail prevail over truck transport (Reynolds 2000). Estimates range from US$ (2005) 6 to 10 /m^3 for ocean shipping; US$ 20 to 90 /m^3 for barge; US$ 10 to \$40 /m^3 for rail and US$10 – 20 /$m^3$ for trucks used over short distances [TSU: figures will need to be adjusted to 2005 US$/$m^3$].

In Brazil, depending on the origin of the biofuel, the costs of transporting ethanol from the producing regions to export ports is around US$(2005) 35-64 /$m^3$ which also includes storage costs at the terminal (Scandiffio 2008). Ethanol pipelines are being planned to connect main rural producing centres to coastal export ports with an expected cost ranging from US$ 20-29 /m^3, 70% less than by road and 45% less than by rail (CGEE 2009).

8.2.3.6 Case study: Brazil ethanol

Successful integration of liquid biofuels with the oil distribution system began with the inception of the National Alcohol Program in 1975 when the state oil company, Petrobras, was obliged to purchase all alcohol domestically produced, blend it with gasoline, and distribute it nationwide. In 1979, vehicles suitable for use of E100 were produced and sold and Petrobras had to develop and adapt existing infrastructure to deliver this product to all regions. (Ethanol production is regionally concentrated but the fuel is available nationwide). When sugar prices competed with ethanol production, owners of E100 vehicles experienced fuel shortages.

Almost all new small road vehicles sold today are flex-fuel, capable of using bioethanol blends ranging from E20 to E100. Since 2003, the manufacture of flex-fuel engines, the biofuel distribution system and the retailing of blends have all been successful. All gasoline sold for spark-ignition engines has a blended content of 20-23% anhydrous ethanol (by volume). Over the last 30 years a country-wide ethanol storage and distribution system was implemented so that biofuel blends are available in practically all refuelling stations. Ethanol prices to the consumer have declined steadily and remain competitive with gasoline prices in late 2009 / early 2010 when oil fluctuated around US$ 80 /barrel [TSU: figure will need to be adjusted to 2005 US$/barrel].

Since 1990, excess electricity generated in sugar/ethanol plants from CHP systems using the bagasse co-product has been able to be fed into the national grid. Technological improvements, better energy management and co-generation schemes have enabled optimal use of the bagasse. Governmental programmes (PROINFA 2010), regulatory changes, and public auctions for bio-electricity contracts were also introduced to enable this electricity to be sold to local utilities or monitored and dispatched by the national system operator. The greater generation of electricity from bagassecoincides with the dry season and so complements the country's hydroelectric-based system.

In 2008 total installed capacity for bioelectricity production was 3.9 GW, around 3.7% of total electrical capacity. Ethanol production was 495 PJ, equivalent to 85% of the energy in gasoline consumed in that year (EPE 2009).

8.2.5 Autonomous systems

8.2.5.1 Characteristics

To be sustainable, and depending on whether the energy carrier is electricity, hydrogen, or liquid, gaseous or solid fuels, an energy system needs to maintain demand-supply balance over various time frames. When a system is small, the demand-supply balance problem readily emerges so that the energy system has autonomy for the balancing (an autonomous system). The integration of several RE conversion technologies, energy storage options and energy use technologies in a small-scale energy system depends on the site specific availability of RE resources and the energy demand due to geology, climate, and lifestyle. This creates several types of autonomous systems.

- *Power supply*. Different RE generators can each meet a part of an autonomous power system demand to enhance the sustainability of the system in, for example, on an off-grid island. Currently, it is usual that fossil fuel generators are also included to give security, reliability and flexibility of system operation.
- *Power supply in a developing economy*. Single or mixed types of RE generation technologies can form a hybrid power supply system in a remote area for mini-grid or stand-alone off-grid

electrification. A stand-alone hybrid power supply could improve its performance with integration of energy storage technologies (section 8.2.1.4) to overcome RE variability.

- *Buildings.* Remote rural buildings can often benefit from autonomous energy supply systems due to the RE resource usually available and the large distances from the power or gas grids. Urban domestic and commercial buildings are normally independent of integrated RE technology due to the network energy supply, though interest in buildings becoming energy generators is growing (IEA 2009).
- *Specific utilization.* In areas where the provision of commercial energy is not economically available, RE can be beneficial for supplying energy services such as water desalination, water pumping, refrigeration and drying.

8.2.5.2 Options to facilitate integration and deploy autonomous systems

An autonomous RE power system could involve the limited deployment of a single type of RE generation technology such as solar power, or incorporate a portfolio of technologies. The capacity of the RE generation can be increased by the addition of more generation units of similar type, or by adding other types of RE generation technologies to enhance operational flexibility. Fossil fuel generation to maintain the desired supply reliability and flexibility of system operation could, in the future, be displaced by increased flexibility and the integration of energy storage technologies.

In developing economies, the balance between cost and quality is critical when designing and deploying autonomous power supplies particularly in rural areas. The simplest type of remote area power system is a DC supply from stand-alone, solar PV panels to meet small lighting, ventilation, radio and television demands of one or more households. Power can be made available during the night by adding a battery or small petrol or diesel generator. A hybrid wind/solar system may have increased reliability benefits where a wind resource is available and also reduce the battery capacity needed to provide a given level of reliability. Micro-hydro schemes are common in hilly regions to give continuous supply, with storage batteries added to meet peak load demands if required.

Batteries and other energy storage technologies used to enhance the performance of small-scale power supply systems are usually expensive, so capital and operational costs should be carefully evaluated along with the level of reliability desired.

Heat demands, usually met by traditional biomass or fossil fuels, could utilise solar thermal, geothermal or modern biomass (IEA 2007) including improved designs of cooking stoves (section 8.3.2.4). Meeting cooling demands from RE such as solar adsorption technology is not yet fully commercial.

8.2.5.2.1 Technical options

For many autonomous RE systems, (with the possible exception of bioenergy CHP or run-of-river micro hydro schemes but including wind/diesel), energy storage and special energy utilization technologies are an integral part (Lone and Mufti 2008).

Simulation analyses, demonstration tests and commercial operations on the application of energy storage technologies to an autonomous system have been reported. These include demonstrations of pumped hydro systems plus wind integration in the Canary Islands (Bueno and Carta 2006) and PV plus wind with hydrogen storage in Greece (Ipsakis, Voutetakis et al. 2009). For heating or to fuel internal combustion engine driven generators, liquid fuels produced from biomass are comparatively easy to store in a container, as are gaseous fuels in tanks or under pressure.

To enhance value or improve performance, autonomous RE systems can be integrated with special energy utilization technologies that use surplus power only when available including solar stills, humidifiers/dehumidifiers, membrane distillers, reverse osmosis or electro-dialysis water desalinators (Mathioulakis, Belessiotis et al. 2007), water pumps using solar PV arrays and an AC or DC motor (Delgado and Torres, 2007), solar-powered adsorption refrigerator (Lemmini and Errougani 2007), and multi-seeds oil press (Mpagalile, Hanna et al. 2005).

Buildings could be designed to generate as much energy as they consume by installing energy efficiency technologies and on-site power generation. The Net-Zero Energy Commercial Building Initiative of the (USDOE 2008) aims to achieve marketable building designs by 2025. Low-rise buildings have good potential to become autonomous through the combination of air-tight structure, high heat insulation, energy efficient air conditioning, lighting, ventilation, water heating, and high utilization of RE technologies (8.2.5.7). Building-integrated photovoltaics (BIPV) (Bloem 2008), distributed energy systems (IEA 2009) and off-grid operation (Dalton, Lockington et al. 2008) are all now past the demonstration phase of development.

8.2.5.3 Benefits and costs of RE integration design

In autonomous energy systems, the electricity generated is usually more expensive than that from a network where grid connection is available. Integration of different kinds of RE may improve the economy and reliability of the supply (Skretas and Papadopoulos 2007). The viability of autonomous energy systems should be evaluated including the future constraints of fossil fuel supply, current technology innovation , avoidance of infrastructure construction and projected cost reductions (Nema, Nema et al. 2009).

For remote off-grid areas, it is widely recognized that electrification can contribute to rural development through increased productivity per capita; enhanced social and business services such as education, markets, drinking water and irrigation; improved security due to street lighting; decreased poverty; and improved health and environmental issues (Goldemberg 2000; Johansson and Goldemberg 2005; Takada and Charles 2006; Takada and Fracchia 2007). The use of biomass, where resources, including organic wastes, are substantial and sustainable, is inevitable to supply basic services for cooking, lighting and small-scale power generation.

In an autonomous building where several RE technologies can be integrated to provide various services, there is potential to enhance the performance of the system. In China, extensive solar thermal utilization in the building sector has brought environmental, social and economic benefits (Li, Zhang et al. 2007). In Japan, house suppliers, (such as Misawa Home Co. Ltd. and Shimizu Construction Co., Ltd.) sell net-zero energy houses which solely use electricity but compensate for their power consumption by integrated solar PV. An urban autonomous building can benefit from having a green value and non-interruptible power service.

Autonomous energy to supply remote telecommunication facilities is economically feasible in both developed and developing countries. Solar water pumping is at the commercial stage, but not always well deployed in developing countries where it is needed, such as the Algerian Sahara (Bouzidi, M. et al. 2009).

8.2.5.4 Constraints on the rate and extent of deployment

Technological constraints and planning tools. The role of RE technologies is changing from a niche market to having a major role in autonomous energy systems, thereby increasing the need for system integration. For each type of autonomous system, appropriate planning methodologies should be established (Giatrakos, Tsoutsos et al. 2009). The variety of possible RE technologies, including variable generators, makes planning more difficult. To improve planning methodology, databases could be established from RD&D as well as commercial experiences that reflect various combinations of technologies, specific site conditions, and life styles (Amigun, Sigamoney et al. 2008; Himri, Stambouli et al. 2008). In the case of biomass, sustainability criteria should be included (Igarashi, Mochidzuki et al. 2009).

Institutional social constraints and enabling environment. Major constraints can arise as a result of wide-ranging technology specifications and the difficulty of appropriate planning, designing, construction and maintenance which can lead to capital and operational cost increases and various disclaimers following a failure. Establishing standards, certifying products, integrating planning tools and developing a knowledge database could help avoid these problems (Kaldellis, Zafirakis et al. 2009), as could local capacity building and market establishment to give low capital and operational costs (Meah, Ula et al. 2008).

The deployment of RE may require accompanying policy measures (often characterized as "the enabling environment") such as establishing institutions (e.g. energy efficiency and RE agencies), appropriate energy pricing, economic incentives (e.g. subsidies, preferential rates for loans, grants), and fiscal incentives (e.g. lower profit tax, reduction or waiver on import duty) (Chapter 11).

Implementation and operation. RE technologies (except some biomass projects) are capital-cost-intensive compared with operation-cost-intensive fossil fuel conversion technologies. Accordingly, even where an autonomous, integrated system is economically feasible, there can be need for an appropriate financial scheme to remove the barrier of large capital costs. Local employment to operate and maintain autonomous systems can be secured through appropriate training and capacity building programmes.

8.2.5.5 Case studies

8.2.5.5.1 Seawater desalination in a rural area of Baja California, Mexico

Baja California Sur, Mexico is an arid sparsely populated costal state where underground aquifers are over-exploited due to population growth, agricultural demands and booming tourism. Around 70 desalination plants use fossil fuel electricity and there are plans to construct more.

Small-scale desalination using PV is an attractive water supply option for small remote communities in the state. The most successful solar desalination system consists of a PV array, battery bank, and seawater reverse osmosis plant (PFSWRO) to produce 19 m^3/day of freshwater with a total dissolved solids content of < 250 ppm and consuming as little as 2.6 kWh/m^3 of water (Contreras, Thomson et al. 2007). PFSWRO uses an energy recovery device and integrates battery banks to enable 24 hour operation. The balance between continuous, smooth operation and cost minimisation depends on optimizing the integration of battery banks. In the future, further integration of desalination plants and rural electrification could be beneficial for provision of water and energy supplies to remote rural communities.

8.2.5.5.2 The Renewable Energy House, Bruxelles, Belgium.

The aim in refurbishing the offices and meeting facilities of this 140 year-old, 2,800 m² building, was to reduce the annual energy consumption for heating, ventilation and air conditioning by 50% compared to a reference building, and to meet the remaining energy demand for heating and cooling using solely RE sources. Key elements of the heating/cooling systems are 85 kW and 15 kW biomass wood pellet boilers; 60 m² solar thermal collectors (half being evacuated tubes and half flat plates); and four 115 m deep geothermal borehole loops connected to a 24 kW ground source heat pump (GSHP) in winter. This is used in summer for cooling, but most cooling comes from a 35 kW capacity (at 7-12°C), thermally-driven, absorption cooler driven by relatively low temperature solar heat (85°C) and a little electrical power for the control and pumping circuits (Fig. 8.22).

In winter, the heating system mainly relies on the GSHP biomass and the pellet boilers since the solar contribution is low. However, when available, solar heat reduces pellet consumption since both heat the same water storage tank. The GSHP operates on a separate circuit. In summer, since solar radiation and cooling demands usually coincide, the solar absorption cooler provides most of the cooling, (backed up on cloudy days by heat from the biomass boiler). The GSHP borehole loops absorb any excess low-grade heat and thus serve as a seasonal heat storage system (EREC 2008).

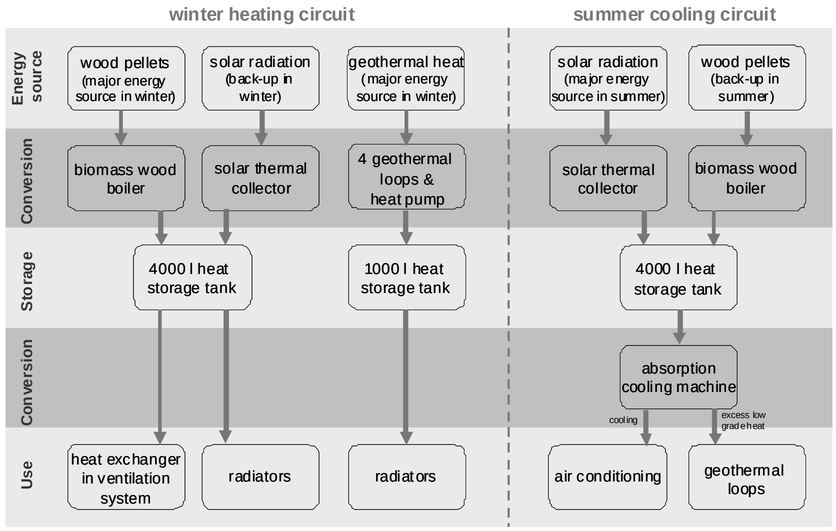

Figure 8.22: Renewable heating and cooling system in an autonomous building (EREC 2008).

8.2.5.5.3 Wind/hydrogen demonstration, Utsira, Norway

An autonomous wind/hydrogen energy demonstration system located on the island of Utsira, Norway was officially launched by Norsk Hydro (now Statoil) and Enercon (a German wind turbine manufacturer) in July 2004. The main components of the installed system are a 600 kW rated wind turbine (with cut-off set at 300 kW), water electrolyser to produce 10 Nm^3/h hydrogen, 2400 Nm^3 of hydrogen storage (at 200 bar), 55 kW hydrogen engine, and a 10 kW PEM fuel cell. The innovative system gives 2-3 days of full energy autonomy supplying 10 households on the island (Ulleberg, Nakken et al. 2010).

Operational experience and data collected from the plant for 4-5 years showed the specific energy consumption for the overall hydrogen production system (including electrolyzer, compressor, inverter, transformer, and auxiliary power) at nominal operating conditions was about 6.5 kWh/Nm^3, equivalent to an efficiency of about 45% (based on lower heat value). The efficiency of the hydrogen engine/generator system was about 25% at nominal operating conditions. Hence, the overall efficiency of the hydrogen system (AC-electricity to hydrogen to AC-electricity) assuming no storage losses was only about 10%. If the hydrogen engine is replaced by a new 50 kW PEM fuel cell, the overall hydrogen storage efficiency would increase to about 16-18%. Replacing the electrolyser by a more efficient unit (e.g. a PEM electrolyzer or a more advanced alkaline design), the overall system efficiency would increase to around 20% (Ulleberg, Nakken et al. 2010).

This low efficiency illustrates the challenge for commercial hydrogen systems. Nevertheless, the project demonstrated that it is possible to supply remote area communities with wind power using hydrogen as the energy storage medium but that further technical improvements and cost reductions need to be made before wind/hydrogen-systems can compete with commercial solutions such as a wind/diesel hybrid. Areas for improvement include the overall wind energy utilization since only 20% is currently utilized. This can best be achieved by installing more suitable and efficient load-following electrolyzers that allow for continuous and dynamic operation. Surplus wind energy could also be used to meet local heating demands, both at the plant and in the households. In addition, the hydrogen (and possibly the oxygen) could be utilized in other local applications, e.g. as a fuel for local vehicles and boats.

More compact hydrogen storage systems and more robust and less costly fuel cells need to be developed before wind/hydrogen-systems can be technically and economically viable.

8.3 Strategic elements for transition pathways

For each of the transport, buildings, industry, and primary production sectors, in order to gain greater RE deployment, strategic elements and non-technical issues need to be better understood. Preparing transition pathways for each element could enable a smooth integration of RE with the conventional energy systems to occur. Multi-benefits for the energy end-users should be the ultimate aim.

In the IPCC 4th Assessment Report -Mitigation (Metz, Davidson et al. 2007) the economic potentials for each of the transport (Chapter 5); residential and commercial buildings (Chapter 6); industry (Chapter 7); and agriculture (Chapter 8) sectors were analysed in detail (Fig. 8.23). The substitution of fossil fuels by RE sources was included in the energy supply sector (chapter 4), together with fuel switching, nuclear power and CCS (carbon dioxide capture and storage).

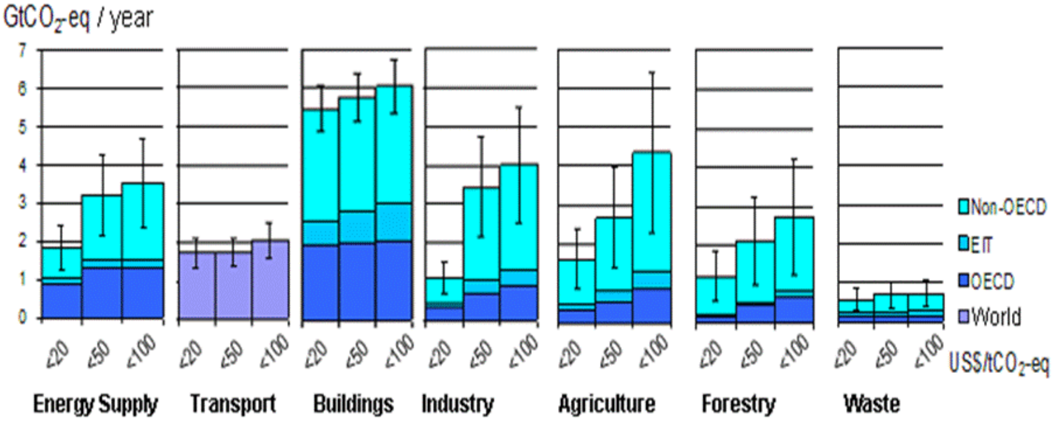

Figure 8.23: Estimated economic, mitigation potential ranges for energy supply and end-use sectors, above the assumed baseline for different regions as a function of the carbon price in 2030 and based on end-use allocations of emissions including from electricity generation.

The IPCC 4th Assessment Report was based mainly on data collected from 2004 or before as published in the latest literature at the time of writing. Since then, RE technology developments have continued to evolve and there has been increased deployment due to improved cost-competitiveness, more supporting policies, and increased public concern at the threats of energy security and climate change. In the following sections, for each sector the current status of RE use, possible pathways to enhance its increased adoption, the transition issues yet to be overcome, and future trends, are discussed. Regional variations are included, particularly for the building sector where deploying RE technologies differs markedly with the present state of urban development.

8.3.1 Transport

8.3.1.1 Sector status and strategies

The direct combustion of fossil fuels for transport consumes 19% of global primary energy use, produces approximately 23%[10] of GHG emissions and between 5-70% of air pollutant emissions depending on the pollutant and region (IEA 2009). Light duty vehicles (LDVs) account for about half of all transport energy use worldwide, with heavy duty vehicles (HDVs) 24%, aviation 11%,

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[10] 23% in 2005 on a well-to-wheel basis

shipping 10%, and rail 3% (IEA 2009). Recent studies suggest that decarbonising and improving the efficiency of the transport sector will be critically important to achieving long-term, deep cuts in carbon emissions as required for climate stabilization (IEA 2009).

Energy supply security is also a serious concern for the transport sector. Demand for mobility is growing rapidly with the number of motorized vehicles projected to triple by 2050 (IEA 2009). Globally, about 94% of transport fuels come from petroleum, a large fraction of which is imported (EIA 2009).

To help meet future goals for both energy supply security and GHG reduction, oil use will need to be radically reduced over a period of several decades. Recent scenario studies (Yang 2007; IEA 2008; NRC 2008) (McKinsey *et al*., 2008) suggest that a combination of approaches will be needed to accomplish 50-80% reductions in transport-related GHG emissions by 2050 (compared to current values) whilst meeting the projected growth in demand and diversifying the primary energy supply (IEA 2009)[11].

- *Reduction of travel demand* (in terms of less *vehicle kms travelled*) might be best achieved by encouraging greater use of car-pooling, cycling and walking, combining trips or tele-commuting. In addition, city and regional "smart growth" practices could reduce GHG emissions as much as 25% by planning cities with denser population so that people do not have to travel as far to work, shop and socialize (Johnston and [NameOtherAuthors?] 2007; PCGCC 2010).
- *Improving efficiency* (in terms of reduced *MJ per km*) can be improved by shifting to more energy efficient modes of transport, such as from LDVs to mass transit (bus or rail[12]), or from trucks to rail or ships[13] (IEA 2009). Vehicles can be made more energy efficient by reducing vehicle weight, streamlining, and improving designs of engines, transmissions and drive trains, such as hybrid electric vehicles (HEVs), turbo-charging and down-sizing. Electric drive vehicles, employing either batteries or fuel cells, can be more efficient than their internal combustion engine (ICE) counterparts, but the full well-to-wheel efficiency will depend on the source of the electricity or hydrogen (Kromer and Heywood 2007; NRC 2008). Consumer acceptance of high efficiency drive trains and lighter cars will depend on a host of factors including vehicle performance and purchase price, fuel price, and advancements in materials and safety. In the heavy duty sub-sector for freight movement, and in aviation, there is also promise of significant efficiency improvements.
- *Replacing petroleum-based fuels with low or near-zero carbon fuels*. These include renewably produced biofuels, and electricity or hydrogen produced from low carbon sources such as renewables, fossil energy with CCS, or nuclear power. Alternatives to petroleum-based fuels have had limited success thus far since the total number of alternative-fuelled passenger vehicles are currently less than 1% of the global on-road vehicle fleet (IEA 2009). Alternative fuels, including electricity for rail, typically represent about 5-6% of total transport energy use (IEA 2009). Exceptions include: Brazil, where around 50% (by energy content) of transport fuel for LDVs (IEA 2007), representing about 15% of total energy use, is from sugar cane ethanol (EIA 2009); Sweden, where imported ethanol is being encouraged; and the US where ethanol,

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[11] In IEA scenarios, vehicles become about twice as efficient by 2050 and in the "Blue Map" scenario (50% GHG reduction by 2050), conventional gasoline and diesel LDVs are largely replaced. GHG emission reductions come from a mix of improved efficiency (which accounts for at least half of the reductions) and alternative fuels (biofuels, electricity and hydrogen) making up 25-50% of total transport fuel use in 2050. Liquid biofuels are used extensively in the HDV, aviation and marine sections

[12] Assuming that mass-transit is operating at relatively high capacity.

[13] On a passenger-km basis, the transport modes with the lowest GHG intensity are rail, bus and 2-wheelers, the highest being LDVs and aviation. For freight, shipping is the lowest GHG intensity mode on a tCO_2-km basis, followed by rail, and then, by at least an order of magnitude higher, HDVs and air.

derived from corn or imported from Brazil, is currently blended with gasoline up to 10% by volume in some regions, but still only accounts for about 3% of total US transport energy use (USDOE 2009). Compressed natural gas (CNG) is widely used in LDV fleets, lead by Pakistan, Argentina, Iran, Brazil, and India (IANGV 2009). Liquefied petroleum gas (LPG) is also used in several countries. Sweden is encouraging the use of biogas for vehicles (IEA 2010)[14] and electricity also makes a material contribution to the transport sector in many countries, mostly limited to rail. The context for alternative fuels is rapidly changing and a host of policy initiatives in Europe, North America and Asia are driving towards lower carbon fuels and zero-emission vehicles.

8.3.1.2 Renewable fuels and light-duty vehicle pathways

The potential exists to make a transition in the transport sector using large quantities of RE as fuels (IEA 2009). In this section, future pathways for RE fuels and vehicle are reviewed, each with different environmental impacts, costs and benefits from a lifecycle perspective. A variety of more efficient vehicles and alternative fuels have been proposed including gasoline and diesel plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (EVs), hydrogen fuel cell electric vehicles (HFCVs), and liquid and gaseous biofuels. Possible fuel/vehicle pathways (Fig. 8.24) begin with the primary energy source, its conversion to an energy carrier (or fuel), and end-use in a vehicle power unit.

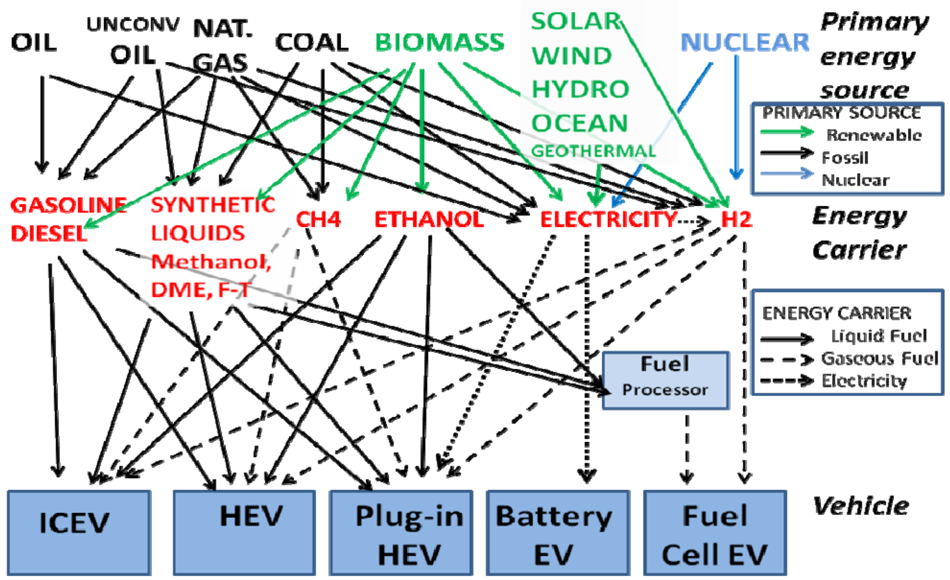

Figure 8.24: Possible fuel/vehicle pathways, from primary energy sources, through energy carrying fuels (red) to vehicle end-use options, and showing RE resources (green).

Notes: F-T= Fischer-Tropsch process. “Unconventional oil” refers to oil sands, oil shale, and heavy crudes.

Technical details of liquid and gaseous RE fuel production and delivery are given in Chapters 2 and sections 8.2.3 and 8.2.4. This section focuses on how the different RE pathways can be integrated into the present transport system. Metrics include cost, GHG emissions from well-to-wheels (WTW), (made up of “well-to-tank” emissions upstream of the vehicle plus “tank-to-wheels” vehicle-related emissions), energy use, and air pollutant emissions.

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[14] In Sweden 19% of biogas produced was used in vehicles in 2006, but this is still only about 1% of total transport energy use**.**

Primary energy use and GHG emissions vary with different fuel/vehicle options. WTW analyses (MacLean and Lave 2003; CONCAWE 2007; Bandivadekar, Bodek et al. 2008; Wang 2008) account for all the emissions including those associated with primary resource extraction, processing and transport, conversion to a useful fuel, distribution and dispensing, and vehicle use, although land use change impacts from biofuel feedstock production are often not included (Chapter 2). Air quality and energy security are other considerations for future transport pathways and sustainability issues, such as land-use, water and materials requirements, that may impose constraints. Commercialising new vehicle-drive technologies could require large amounts of scarce, hard to access mineral resources. For example, automotive fuel cells require platinum, HEV motors require high-power, lightweight magnets; EVs and HFCVs need neodymium and lanthanum; and the most likely next generation of advanced, lightweight, high-energy-density batteries require lithium. Composite sustainable fuel indicators include a variety of factors in addition to GHG emissions (Zah, Böni et al. 2007).

8.3.1.2.1 Status and prospects - vehicle technology

A variety of alternative vehicle drive trains could use RE based fuels including advanced ICE vehicles using spark-ignition or compression-ignition engines (ICEVs), HEVs, PHEVs, EVs, and HFCVs. Several recent studies have assessed the performance, technical status, and cost of different vehicle types (CONCAWE 2007; Kromer and Heywood 2007; Bandivadekar, Bodek et al. 2008; IEA 2009; Plotkin and Singh 2009). Fuel economy and incremental costs of alternative-fuelled vehicles based upon these studies have been compared (Figs. 8.25 and 8.26). Since each study employed different criteria and assumptions for vehicle design and technology status, the development timeframes varied between 2010 and 2035, and since not all vehicle/fuel pathways were covered in all studies, the results have been normalised to those for an advanced, gasoline ICEV (as one was defined in each study). The relative efficiency assumptions for different vehicle types varied among the studies, especially for less mature technologies, although the overall findings were consistent. Several trends are apparent.

- There is significant potential to improve fuel economy by adopting new drive trains and more advanced engines.
- Hybrid vehicles and adoption of electric drives give increased efficiency and improved fuel economy by 15-70% over conventional gasoline ICEVs.
- Although still under development and in demonstration phase, HFCVs may run 2 to 2.5 times more efficiently than gasoline ICEVs.
- EVs could operate up to 2.7 to 3.5 times as efficiently as gasoline ICEVs, not including electric power generation inefficiencies.
- On a total WTW fuel cycle basis, the relative efficiency improvements for HFCVs and EVs are considerably less when electricity generation and hydrogen production losses are included.
- Losses related to electricity generation, transmission and distribution range between approximately 40-80%, depending on the source of power. A similar loss range occurs for hydrogen production, depending on the energy feed, conversion technology, and distribution infrastructure.
- There is uncertainty in the fuel economy and cost projections for HFCVs and EVs, both of which are still far from high volume commercialization.
- In general, the higher the fuel economy, the higher the vehicle price (assuming size and performance are similar).

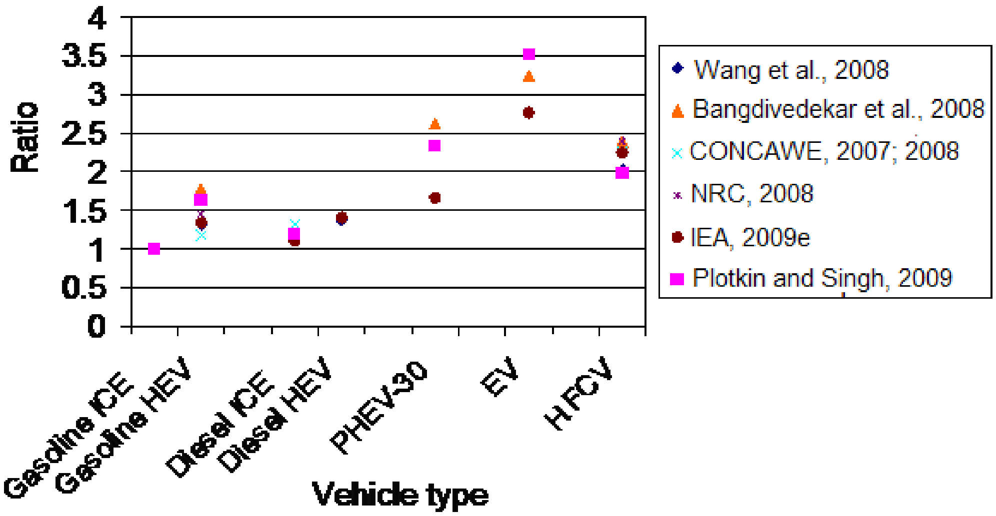

Figure 8.25: Relative fuel economies of future alternative-fuelled light duty vehicles compared to advanced spark ignition, gasoline-fuelled, ICE vehicles, based on various studies.

Note: The values represent tank-to-wheel energy use. Well-to-tank energy use should also be considered (8.3.1.2). Typical well-to-tank energy losses are 5-15% for gasoline and diesel; 60% for biofuels; 45-80% for electricity; and 40%-90% for hydrogen (Wang 2008).

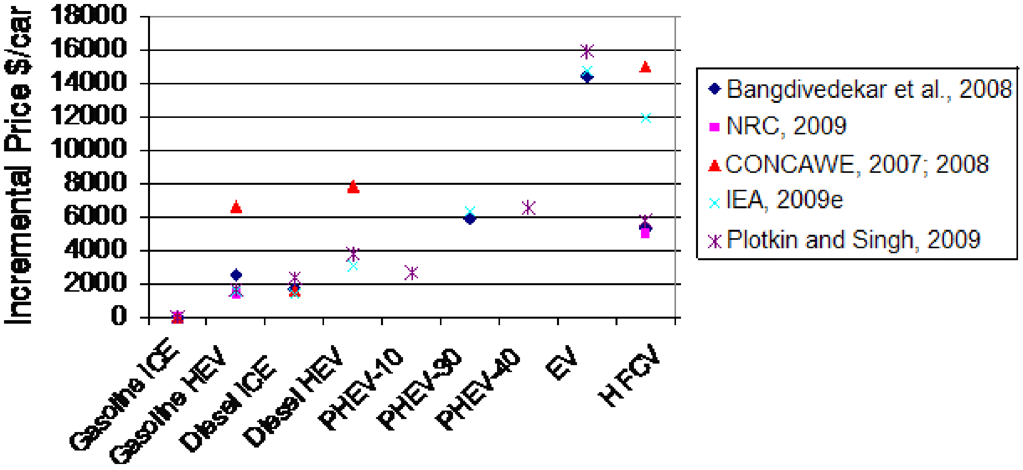

Figure 8.26: Relative incremental retail price for alternative light duty vehicles compared to advanced gasoline, spark ignition, ICE vehicles

Notes: Bandivedekar et al. (2008) gave projections for 2035. NRC (2009) assumed mature technologies with cost reductions due to experience learning and mass production post-2025. CONCAWE (2007 and 2008) were for 2010+ technologies; IEA (2009) and Plotkin and Singh (2009) were for 2030 technology projections.

Millions of vehicles capable of running on liquid biofuels or biomethane are already commercially available and in the global fleet. The cost, weight, and life of present battery technologies are the main barriers to both EVs and PHEVs but the vehicles are undergoing rapid development, spurred by recent policy initiatives worldwide. Several companies have announced plans to commercialize them within the next few years, albeit in relatively small numbers initially (tens of thousands of vehicles per year). Electric two-wheel motor-bikes and scooters are a large and fast-growing market in the developing world, especially in China with 20 million annual sales in 2007 (ICCT 2009). They have significant potential for fuel efficiency improvement and GHG reduction. HFCVs have been demonstrated, but are unlikely to be fully commercialized until at least 2015-2020 due to barriers of fuel cell durability, cost, on-board hydrogen storage and hydrogen infrastructure availability and cost. The timing for commercializing each technology is discussed below (8.3.1.4).

8.3.1.3 Transition issues for light-duty transport

To meet future energy security and GHG emission reduction goals, the transport sector will need to be fundamentally transformed (8.3.1.1). Historically, major changes in transport systems, such as building canals and railroads, paving highways, and adopting gasoline cars, have taken many decades to complete for several reasons.

- Passenger vehicles have a relatively long lifetime (15 years average in the US but longer elsewhere). Even if a new technology rapidly moved to 100% of new vehicle sales, it would take years for the vehicle stock to “turn over”. In practice, adoption of new vehicle technologies occurs slowly and can take 25 to 60 years for an innovation to be used in 35% of the on-road fleet (Kromer and Heywood 2007). For example, research into gasoline HEVs in the 1970s and 1980s led to a decision to commercialize in 1993 with the first vehicle becoming available for sale in 1997 in Japan. Over 13 years later, HEVs still represent only about 1% of new car sales and less than 0.5% of the worldwide fleet (although low oil prices during this period were maybe a factor). This slow turnover rate is also true for relatively modest technology changes such as the adoption of automatic transmissions, intermittent windscreen wipers and direct fuel injection. The timeframe for new technologies relying on batteries, fuel cells, or advanced biofuels could be even longer since they all need further RD&D investment and international standardization before they can be fully commercialized. Further cost reductions would then be needed to achieve wide customer acceptance.
- Changing fuel supply infrastructure, especially if switching on a major scale from liquids to gaseous fuels or electricity, will require a substantial amount of capital and take many decades to complete (IEA 2009; Plotkin and Singh 2009). Developing new supply chains for RE, and replacing existing fossil fuel systems, will take time and require close co-ordination among fuel suppliers, vehicle manufacturers and policy makers.

Each fuel/vehicle pathway faces its own transition challenges which can vary by region. In terms of technology readiness of fuels and vehicles, challenges include infrastructure compatibility, consumer acceptance (costs, travel range, refuelling times, safety concerns), primary resource availability for fuel production, life-cycle GHG emissions, and environmental and sustainability issues including air pollutant emissions and demand for water, land and materials.

8.3.1.3.1 Liquid biofuel pathways

Biofuels are generally compatible with ICEV technologies. In fact, many ICEVs already use liquid biofuels whereas only a small fraction have been adapted to run on gaseous fuels or hydrogen. HEVs introduced for gasoline vehicles can also use ethanol blends. However, most of the existing gasoline and diesel ICEV fleet can only operate on relatively low biofuel blends up to 10% by volume of ethanol or 5% of biodiesel, to avoid possible adverse effects of higher blends on the engine. An increasing number of flexible fuel vehicles (FFVs) in the US, Brazil, and Sweden can use higher blends of ethanol (up to 85%) or revert to gasoline.

Biomass can be converted to liquid fuels using many different routes (Chapter 2). First generation processes are commercially available and 2nd generation and more advanced processes, aiming to convert non-food, cellulosic materials and algae are under development (8.2.4). Second generation biofuels have potential for lower WTW GHG emissions than petroleum derived fuels, but these technologies are still several years from market (IEA 2008).

An advantage of some advanced liquid biofuels is their relative compatibility with the existing liquid fuel infrastructure and ease of blending with petroleum-derived fuels. Low liquid biofuels blends have similar properties to neat gasoline or diesel with similar engine performance and refuelling times. They do not require new vehicle types and can be relatively “transparent” to the consumer. Ethanol, under some circumstances, cannot be shipped through existing fuel pipelines (8.2.4) and in some countries, has limits on the concentrations that can be blended. It would likely need its own distribution and storage systems, as well as dispensing pumps for blends beyond E10. Fuel costs may therefore be the main factor determining consumer acceptance. In Brazil, for example, flex-fuel vehicle users select their fuel based on price. Reduced range and reduced fuel economy with ethanol and, to a lesser extent, biodiesel, can also be a factor in consumer acceptance.

Primary biomass resource availability can be a serious issue for biofuels. Recent studies (IEA 2009; Plotkin and Singh 2009) have assessed the national or global potential for biofuels to displace petroleum products. Environmental and land-use concerns could limit production to 20-25% of total transport energy demand. Given that certain transport sub-sectors such as aviation and marine require liquid fuels, it may be that biofuels will be used primarily for these applications, whilst electric drive train vehicles (EVs, PHEVs, or HFCVs), if successfully developed and cost effective, might dominate the LDV sector.

8.3.1.3.2 Biomethane pathways

Biogas and landfill gas (produced from organic wastes and green crops, Chapter 2) can be purified and injected into existing natural gas distribution systems (8.2.3). Spark-ignition ICEVs designed or converted to run on CNG can also be run on biomethane. Biogas would first need the CO_2 to be stripped to give greater range per storage cylinder refill, and H_2S also stripped to reduce risk of engine corrosion.

8.3.1.3.3 Hydrogen/fuel cell pathways

Hydrogen is a versatile energy carrier that can be produced in several ways (8.2.3). WTW GHG emissions vary for different hydrogen fuel/vehicle pathways, but both RE and fossil hydrogen pathways can offer reductions compared to gasoline vehicles (8.3.1.4).

Although hydrogen can be burned in a converted ICEV, more efficient HFCVs are attracting greater R&D investment by engine manufacturers. Most of the world’s major automakers have developed prototype HFCVs, and several hundred of these vehicles, including buses, are being demonstrated worldwide. HFCVs are currently very costly, in part because they are not yet mass produced and fuel cell lifetimes are not yet adequate. It is projected that the costs of FCVs will fall with further improvements resulting from R&D, economies-of-scale from mass production, and learning experience (NRC 2008).

HFCVs could match current gasoline ICEVs in terms of vehicle performance and refuelling times. The maximum range of present-day HFCV cars of about 500 km is acceptable, but hydrogen refilling availability and the high cost of both vehicle and fuel remain key barriers to consumer acceptance. Hydrogen is not yet widely distributed to consumers in the same way as electricity, natural gas, gasoline, diesel or biofuels are. Bringing hydrogen to a large numbers of vehicle owners would require building a new refuelling infrastructure over several decades (8.2.3).

Hydrogen can be produced regionally in industrial plants or locally on-site at vehicle refuelling stations or in buildings. The first steps to provide hydrogen to HFCV test fleets and demonstrate refuelling technologies in mini-networks are in place in Iceland and being planned elsewhere through projects such as the California Hydrogen Highways Network, the British Columbia Hydrogen Network, the European "HyWays" Hydrogen Roadmap, and Norway's "Projects in Europe". System level learning from these programmes is valuable and necessary, including development of safety codes and standards. In the US, a mix of low carbon resources including natural gas, coal (with CCS), biomass, and wind power could supply ample hydrogen (NRC 2008). The primary resources required to provide sufficient fuel for 100 million passenger vehicles in the US using various gasoline and hydrogen pathways have been assessed (Ogden and Yang 2009). For example, enough hydrogen could be produced from wind-powered electrolysis using about 13% of the technically available wind resource. However, the combined inefficiencies of making the hydrogen via electrolysis from primary electricity sources, then converting it back into electricity on a vehicle via a fuel cell, loses more than 60% of the original RE inputs. Electricity is used more efficiently in an EV or PHEV but hydrogen might be preferred in large vehicles requiring a long range and fast refuelling times.

Hydrogen production and delivery pathways have a significant impact on the cost to the consumer. In addition, compared to industrial uses, fuel cell grade hydrogen needs to be >99.99% pure and generally compressed to 35 to 70 MPa before dispensing. Using optimistic assumptions, hydrogen at the pump might near-term cost US$(2005) 7-12/kg excluding taxes, eventually reducing to US$(2005) 3 - 4 /kg[15] (NRC 2008; NREL 2009). Given the potential higher efficiency of fuel cell vehicles, the fuel cost per kilometre could become competitive with ICEVs in the future (Kromer and Heywood 2007; NRC 2008).

Several studies (Gielen and Simbolotti 2005; Gronich 2006; Greene, Leiby et al. 2007; NRC 2008) indicated that cost reductions were needed to "buy-down" fuel cell vehicles to market clearing levels (through technological learning and mass production) and to build the associated infrastructure over several decades that could cost hundreds of billions of dollars (8.2.3.5). The majority of this cost would be for the incremental costs of early hydrogen vehicles, with a lesser amount needed for early infrastructure. Even at high oil prices, government support policies may most likely be needed to subsidize these technologies in order to reach cost-competitive levels and gain customer acceptance.

8.3.1.3.4 Electric and hybrid vehicle pathways

While electricity generation from primary energy sources is typically only 20%-55% efficient (or about 18% - 50% once transmission and distribution losses are included), EV drive trains are relatively efficient and battery charging is a reasonably efficient way to store and use primary RE. Combined EV drive train efficiency (85%) and battery charge/discharge efficiencies (90% for electric plug-to-wheels) are in the order of 77%.

The GHG emissions and environmental benefits of EVs depend on the marginal grid mix and the source of electricity used for vehicle charging. For example, the current US grid being 45% dependent on coal, WTW emissions from EVs would not be much of an improvement over efficient gasoline vehicles (Fig. 8.27) whereas for the French electric grid, which uses significant amounts of nuclear power, WTW emissions would be relatively small (Zgheib and Clodic 2009). Various studies have developed scenarios for decarbonising the electricity grid over the next few decades (8.2.1and Chapter 10) that would result in reduced WTW emissions for EVs and PHEVs (EPRI 2007; IEA 2009). With large fractions of RE or low carbon electricity, WTW emissions for EVs could, over time, become much smaller.

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[15] 1 kilogram of hydrogen has a similar energy content to 1 US gallon or 3.78 litres of gasoline

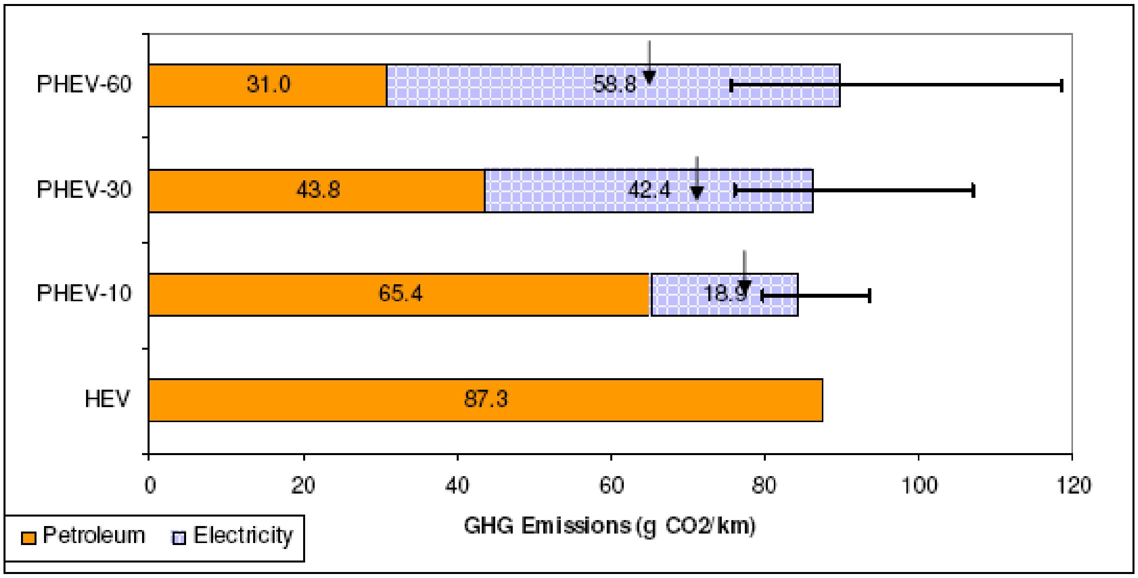

Figure 8.27: Well-to-wheels GHG emissions for gasoline-fuelled hybrid electric vehicles (HEVs) and plug-in hybrids (PHEVs) showing the various ranges when running on electricity only.

Notes: The US06 drive cycle was used to estimate vehicle emissions as CO_2/km. PHEV-10 corresponds to an all-electric range of about 16 km whereas PHEV-60 is around 100 km. Horizontal bars indicate the emission range when using electricity from natural gas to coal-fired power generation. Vertical arrows indicate emission levels from a partially decarbonized grid similar to that in California (Kromer and Heywood 2007).

EV use is currently limited to neighbourhood and niche fleet vehicles, from small go-carts to pick-ups and buses. There is also a limited number of passenger EVs still operating from original models sold by GM, Toyota, Honda and others in the 1990s and early 2000s. Limited commercialization of EVs and PHEVs is planned over the next few years in response to policy measures (Kalhammer, Kopf et al. 2007) with several automobile manufacturers making niche initial offerings. The main transition issue is to bring down the cost and improve the performance of advanced batteries. Today's lithium batteries cost 3-5 times the goal needed to compete with gasoline vehicles on a lifecycle cost basis. Demonstrated lifetimes for advanced lithium battery technologies are 3-5 years, when 10 years is required ideally for automotive applications (Nelson, Santini et al. 2009).

For RE electricity to serve growing EV markets, several innovations need to occur such as development of low-cost power supplies available at the time of recharging EVs. If night-time, off-peak recharging could be employed, new capacity would not necessarily be needed and there may be an adequate temporal match with wind or hydropower resources more than with solar PV. Energy storage may also be a way to balance vehicle electric demand with RE sources. In addition, the distribution grid would need upgrading, possibly including smart grid technologies, to handle the added load. Consumer acceptance is also a key issue. One attraction of EVs is that they could be recharged at home, avoiding trips to the refuelling station. However, home recharging would require new equipment and not all households would be able to conveniently install it, perhaps only 30-50% in the US (Kurani *et al*. 2009). So public recharging point infrastructure may need to be developed in some areas. "Level 1" charging, using a standard plug, and would take several hours, compared with the quick refill time possible with liquid or gaseous fuels. "Level 2" charging could take less time but would require a specialized higher power outlet. Even fast-charge outlets at publically accessible recharging stations might bring batteries to near full-charge only after 10-15 minutes, taking more time than refilling an ICEV. In-home overnight recharging systems might cost US$(2005)700-1300 per charger for level 1 charging and US$800-1900 for level 2 chargers [TSU: figure will need to be adjusted to 2005 US$] (USDOE 2008). An EV is likely to have a shorter range than a similar size ICEV, 200-300 km versus 500-900 km (Bandivadekar, Bodek et al. 2008).

While this range is adequate for 80% of car trips in urban/suburban areas, this factor would make long distance EV travel less practical. This could be overcome by owners of small commuter EVs using rental or community-owned HEV or PHEV vehicles for longer journeys (IEA 2009).

The added vehicle cost for PHEVs, while still significant, is less than for an EV and the range should be comparable to a gasoline HEV. One strategy is to introduce PHEVs initially while developing and scaling up battery technologies for EVs. This could help lead to more cost-competitive EVs. However, HEVs will always be cheaper to manufacture than PHEVs due to the smaller battery capacity, although advances in battery technologies could make them more competitive. Incentives such as low electricity prices relative to gasoline, carbon charges, more inexpensive low-carbon electricity, and first-cost subsidies would be needed to make PHEVs a viable option. Availability of materials for advanced batteries, notably lithium, may be a future concern. EVs have the added ancillary benefit of zero tailpipe emissions which can reduce urban air pollution. However, if the electricity is produced from an uncontrolled source (such as coal plants without proper scrubbers) one source of pollution might simply be substituted for another (Kromer and Heywood 2007; Bandivadekar, Bodek et al. 2008).

8.3.1.4 Comparisons of alternative fuel/vehicle pathways

Different entire fuel/vehicle pathways impact on WTW GHG emissions (Fig. 8.28). For conventional fuels, most of the emissions are “tank-to-wheels” and take place at the vehicles. For electricity and hydrogen, all emissions are “well-to-tank” and the vehicle itself has zero emissions. For RE biofuel pathways, carbon emissions at the vehicle are offset by carbon uptake from the atmosphere by future biomass feedstocks.

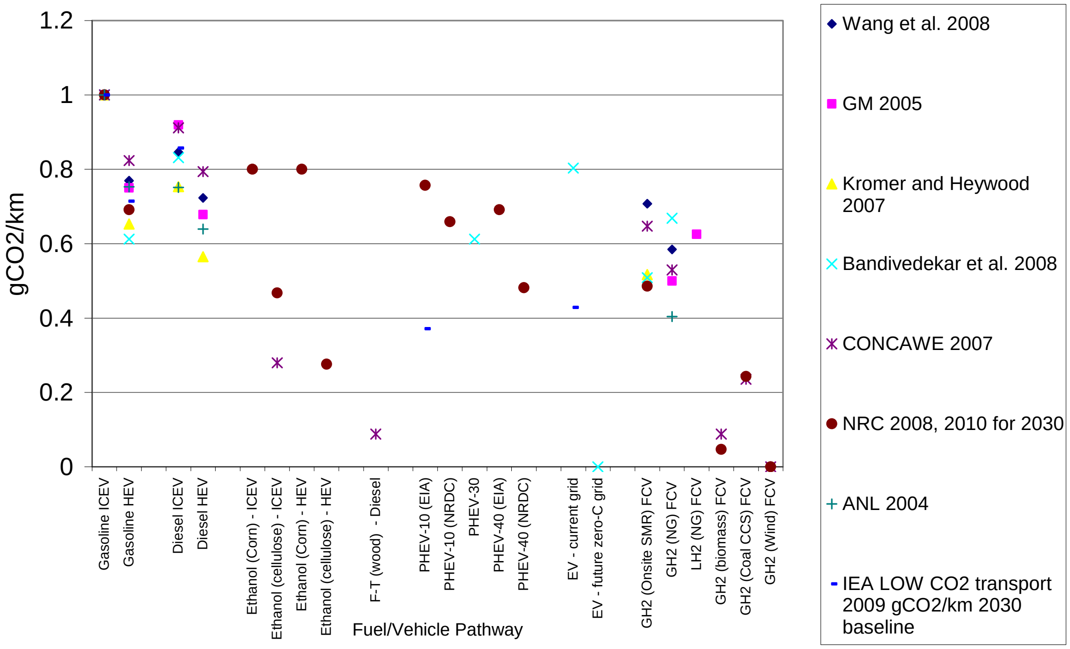

Figure 8.28: Well-to-wheels GHG emissions from several studies of alternative light duty fuel/vehicle pathways.

Note: GHG emissions are normalized to emissions from a gasoline ICEV. For all hydrogen pathways, hydrogen is stored on-board the vehicle as a compressed gas. GH2 = gaseous hydrogen delivery to station; LH2 = liquid hydrogen delivery to station.

8.3.1.5 Comparisons between technologies

Transition issues vary for biofuels, hydrogen, and electric vehicles (Table 8.5). No one option is seen to be a clear “winner” and all will take several decades to implement at the large scale.

Table 8.5: Transition issues for biofuels, hydrogen, and electricity

Technology Status	**Biofuels**	**Hydrogen**	**Electricity**
Vehicles	Millions of flex-fuel vehicles using ethanol, but conventional vehicles still limited to low concentration blends of ethanol (< 10%) or biodiesel (< 5%)	Demonstration HFCVs. Commercial HFCVs: 2015-20	Limited current use of EVs. Demonstration PHEVs, Commercial PHEVs :2010-15. Commercial EVs: 2015-2020.
Fuel production	1st generation: Ethanol from sugar and starch crops, biomethane, biodiesel. 2nd generation: ethanol / diesel/green fuels from cellulosic biomass, biowastes, bio-oils, and algae - after at least 2015.	Fossil H_2 commercial for large-scale industrial applications, but not competitive as transport fuel. Renewable H_2 generally more costly.	Commercial power available. RE electricity generally more costly.
Cost (vs. gasoline vehicles) Incremental vehicle price compared to future gasoline ICEV (US$2005)	Similar vehicle cost to gasoline.	HFCV experience price increment (2035)[16]compared to gasoline ICEV >US$ 5300	Experience price increment compared to gasoline ICEV >US$ 5900 (2035) (PHEVs)

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[16] (Bandevedakar *et al*., 2008)

Fuel cost (US$ /km)	Fuel cost per km competes, if biofuel price per unit energy ~ gasoline price per unit energy.	Fuel cost per kg for H_2 at $3-4/kg (target for mature H_2 infrastructure; may prove optimistic) used in HFCV competes with gasoline at US$ 0.40-0.53/l used in gasoline ICEV, assuming HFCV has 2x fuel economy of gasoline ICEV. Renewable H_2 at least 1.5-3x more expensive.	>US$ 14,000 (2035) (EVs)[16]. Electricity cost per km competes with gasoline cost per km for electricity costs $0.10-0.30/kWh when gasoline costs $0.3-0.9/l (assuming EV has fuel economy 3x gasoline ICEV)
Compatibility with existing infrastructure	Partly compatible with existing petroleum distribution system. Separate distribution and storage infrastructure can be needed for ethanol.	New H_2 infrastructure needed, as well as renewable H_2 production sources. Infrastructure deployment must be coordinated with vehicle market growth.	Widespread electric infrastructure in place. Need to add in-home and public chargers, RE generation sources, and upgrade transmission and distribution (especially for fast chargers).
Consumer acceptance	Fuel cost: alcohol vehicles have shorter range than gasoline. Potential cost impact on food crops and land use. Land and water issues can be a factor.	Vehicle and fuel costs. Safety of on-board gaseous H_2 storage. Fuelling station availability in early markets.	Vehicle initial cost. High electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharge time, but home recharging possible. Significantly degraded performance in extreme climates (cold winters, hot summers).
Existing and potential primary resources	Sugar, starch, oil crops. Cellulosic crops; forest, agricultural and solid wastes. Algae and other biological oils.	Fossil fuels, nuclear, all RE-potential RE resource base is large but inefficiencies and costs of converting to H_2 an issue.	Fossil fuels, nuclear, all RE – potential RE resource base is large.
GHG emissions	Depends on feedstock, pathway and land use issues. Low for fuels from waste residues, and sugarcane. Near-term can be high for corn ethanol. 2nd generation biofuels lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICEVs, WTW GHG emissions for HFCVs using H_2 from natural gas are slightly more to slightly less depending on assumptions. WTW GHG emissions can approach zero for RE pathways.	Depends on grid mix. Using coal-dominated grid mix, EVs, and PHEVs have WTW GHG emissions similar or higher than gasoline HEV. With larger fraction of RE and low carbon electricity, WTW emissions are lower.
Petroleum consumption	Low	Very low	Very low
Environmental and sustainability issues			
Air pollution	Similar to gasoline. Additional issues for ethanol due to permeation of volatile organic compounds (VOCs) through fuel tank seals. Aldehyde emissions.	Zero emission vehicle	Zero emission vehicle.
Water use	More than gasoline depending on feedstock and irrigation needs.	Potentially very low but depends on pathway.	Potentially very low but depends on pathway.
Land use	Might compete with food-for cropland.	Depends on pathway.	Depends on pathway.
Materials use		Platinum in fuel cells. Neodymium and other rare earths in electric motors.	Lithium in batteries. Neodymium and other rare earths in electric motors.

1 Note: Costs quoted do not always include payback of incremental first vehicle costs.

8.3.1.6 Low emission propulsion and renewable options in other transport sectors

8.3.1.6.1 Heavy duty vehicles

Globally, most HDVs consist of freight trucks and long-haul tractor-trailers, which account for about 24% of transport-related energy use and a similar fraction of GHGs (IEA 2009). Other HDVs include buses and off-highway vehicles such as agriculture and construction equipment. As was the case for LDVs, there are several strategies to reduce fuel consumption and GHG emissions:

- partially switching to lower carbon fuels;
- streamlining operational logistics for handling freight and routing by using GPS routing technology, avoiding empty return trips, etc.; and
- further increasing vehicle efficiency, perhaps by up to 30-40% by 2030 (IEA 2009). This can be achieved through more advanced engines, exhaust gas energy recovery (via advanced turbo-charging or turbo-compounding), hybrid vehicles (which may include either electric or hydraulic motors), light-weighting, tyres with lower rolling resistance, improved truck-trailer integration for better aerodynamics, more efficient driving behaviour, optimized automatic gear shifting, speed reduction, and use of more efficient auxiliary power units (APUs) decoupled from the power train.

Today, about 85% of freight-truck fuel is diesel, with the remainder gasoline. Integrating biofuels into the fuel mix would be the most straight forward RE option. The IEA (IEA 2008) expects 2nd generation biofuels to become a more significant blend component in diesel fuel for trucks, possibly reaching as high as 20-30% by 2050. Due to range and resulting energy storage requirements for long-haul HDVs, use of other lower carbon alternatives such as CNG, LPG, compressed biogas, hydrogen (for either HFCVs or ICEVs), or electricity would likely be limited to urban or short-haul HDVs, such as buses, refuse trucks, and delivery trucks. LNG might also become an option for freight transport. Another potential use of low carbon H_2 or electricity might be to power on-board fuel cell APUs or charge batteries, although neither of these options is cost effective yet.

The reduction of fuel consumption and GHG emissions in HDVs may be more difficult than for LDVs due to slower vehicle turnover, faster growth in vehicle km t (VKT), less discretionary freight movement, and inherent economic drivers that continuously aim to minimize life cycle HDV costs. Because many HDVs are purchased for fleet operations, there could be an opportunity to integrate alternative fuels and vehicles by providing fleet-wide support for new fuelling infrastructure, technology maintenance and, if needed, driver training. According to the IEA's baseline scenario (IEA 2008), HDV energy use by 2050, even with improved energy efficiency of about 20%, is projected to increase by 50% as the quantity of worldwide freight moved by trucking doubles. Most of this growth will occur in non-OECD countries.

8.3.1.6.2 Aviation

Aviation energy demand accounted for about 11% of all transport energy in 2006 and could double or triple by 2050 (IEA 2009). Rapid growth of aviation is mainly driven by the increase of air traffic volumes for both passenger and freight traffic and the fact that aviation boasts the highest energy and GHG intensity of all transport modes. Efficiency improvements can play an important role in reducing aviation energy use by 30-50% in future aircraft (IEA 2009). These include improved aerodynamics, airframe weight reduction, higher engine efficiency, and improvements in operation and air traffic control management to give higher load factors, better routing, and more efficient ground operations at airports (including more gate electrification and use of low carbon-fuelled service vehicles) (TRB 2009). Although reductions in energy intensity (energy use per passenger- or per cargo tonne- kilometre) can be substantial, they will not sufficiently decouple fuel demand growth from activity growth to avoid large increases in fuel use since about 90% of fuel use and

GHG emissions occur in flight, mostly at cruising altitude (TRB 2009). Slow fleet turnover, every 30 years on average (IEA 2009; TRB 2009), will delay the penetration of advanced aircraft designs.

Aircraft will continue to rely mainly on liquid fuels due to the need for high energy density fuels in order to minimize fuel weight and volume. In addition, due to safety, the fuels need to meet more stringent requirements than for other transport modes, particularly thermal stability to assure fuel integrity at high engine temperatures and to avoid freezing or gelling at low temperatures; specific viscosity; surface tension; ignition properties; and compatibility with aircraft materials. Compared to other transport sectors, aviation has less potential for fuel switching due to these special fuel requirements. In terms of RE, various aircraft have already flown test flights using various biofuel blends, but significantly more processing is needed than for road fuels to ensure that stringent aviation fuel specifications are met. IEA scenarios range from a few percent up to 30% biofuel use in aviation by 2050 (IEA 2009).

Liquid hydrogen is another long-term option, but faces significant hurdles due to its low volumetric energy density. Fundamental aircraft design changes to accommodate cryogenic storage, and distribution infrastructure hurdles at airports. The most likely fuel alternatives, but not necessarily low carbon, are synthetic jet fuels (from natural gas, coal or biomass) since they have similar characteristics to conventional jet fuel.

8.3.1.6.3 Maritime

Marine transport, the most efficient mode for moving freight, currently consumes about 9% of total transport fuel, 90% of which is used by international shipping (IEA 2009). Ships rely mainly on heavy fuel (“bunker”) oil (HFO), but lighter marine diesel oil is also used. HFO accounts for nearly 80% of all marine fuels. The sulphate emissions that create aerosols may actually mitigate GHG impact by creating a cooling effect. However, future regulations will require lower sulphur marine fuels. An expected doubling to tripling of shipping transport by2050, coupled with ever more stringent air quality regulations aimed at reducing particulate emissions through cleaner fuels, will lead to greater GHG emissions from this sector.

Due to a fragmented industry where ship ownership and operation can occur in different countries, as well as slow fleet turnover (typical ship replacement occurs about every 30 years), energy efficiency across the shipping industry has not improved at the same rate as in the HDV and aviation sectors. Hence, there exist significant opportunities to reduce fuel consumption through a range of technical and operational efficiency measures (IEA 2009; TRB 2009) such as improvements in:

- vessel design (e.g., larger, lighter, more hydro-dynamic, lower drag hull coatings);
- engine efficiency (e.g., diesel-electric drives, waste heat recovery, engine derating);
- propulsion systems (e.g., optimized propeller design and operation, use of sails or kites);
- APUs; and
- operation (e.g., speed reduction, routing optimization, better fleet utilization, reduced ballast).

These measures could potentially reduce energy intensity by as much as 50-70% for certain ship types (IEA 2009).

The key application of RE in marine transport could be through the use of biofuels. Existing ships could run on a range of fuels, including blends of lower quality such as low cost bio-crudes (pyrolysis oil from biomass). Engines would probably need to be modified, similar to HDV road vehicles, to operate on high blend (80-100%) biofuel mixtures. Other RE and low-carbon options could include the use of on-deck hybrid solar PV and micro-wind systems to generate auxiliary power, solar thermal systems to generate hot water or space heating or cooling, and electric APU systems plugged in to a RE grid source while at port.

8.3.1.6.4 Rail

Although rail transport accounts for only a small fraction (~2% in 2005) of global transport energy use, by 2050 rail freight volume is expected to increase by up to 50% with most of this growth occurring in non-OECD countries (IEA 2009). Rail moves more freight and uses an order of magnitude less energy than trucking due to its much higher efficiency (IEA 2009). Rail transport is primarily powered by diesel fuel (almost 90% of rail energy use in 2005), with the balance of the rail network mostly electrified (IEA 2009). Growth in high-speed electric rail technology continues rapidly in Europe, Japan, and elsewhere. As with shipping, the use of high sulphur fuels has helped to mitigate net GHG emissions due to the negative radiative forcing effect of sulphates, but this trend has other negative environmental consequences and will likely decrease with stricter clean fuel regulations.

Rail sector efficiency increases of up to 20-25% are possible (IEA 2009; TRB 2009). Options include:

- upgrading locomotives to more efficient diesel engines, hybrids, and APUs;
- increasing load factors by reducing the empty weight of the rolling stock, lengthening trains, and using double-stacked containers; and
- operational improvements such as operator training, optimized logistics and reduced idling.

The two primary pathways for RE penetration in rail transport are through increased use of biodiesel and renewable “green” diesel, which may account for 2-20% of rail fuel use in 2050 (IEA 2009) and a shift towards electrification. Compared to their diesel counterparts, all-electric locomotives can improve life cycle efficiency by up to 15%, (or less if compared to a diesel hybrid-electric drive system that includes battery storage), and further reduce GHG emissions as electricity generation switches to RE and/or nuclear power. Although the use of hydrogen fuel cells may be limited due to range, energy storage, and cost issues, the challenges for installing fuel cells on locomotives appear to be fewer than for passenger HFCVs. Compared with LDVs, a rail system provides more room for H_2 storage, offers economies of scale for larger fuel cell systems, and uses the electric traction motors already in diesel-electric locomotives.

8.3.1.7 Future trends

Perhaps the most important single trend facing the transport sector is the projected high growth of vehicle numbers worldwide which is expected to triple from the 700 million LDVs today by 2050 (IEA 2008). Meeting this demand while achieving a low carbon, sustainable and secure energy supply, will require rapid technology advancements that are offered in vehicles that are accepted by the public, strong policy initiatives, monetary incentives, and the willingness of customers to pay additional costs. There is scope for RE transport fuel use to grow significantly over the next several decades, playing a major role in this transition.

In the future, a wider diversity of transport fuels and vehicle types is likely. These could vary by geographic region and transport sub-sector. For applications such as air and marine, liquid fuels are probably the only practical option. In the LDV sector, increased use of electric drive train technologies has already begun, beginning with HEVs, progressing to PHEVs and EVs and HFCVs (IEA 2008). Historically, the electric and transport sectors have been completely separate, but, through grid-connected EVs, they are likely to interact in new ways by charging battery vehicles or, possibly, “vehicle-to-grid” electricity supply (8.2.1.6) (McCarthy, Ogden et al. 2008)

Ancillary environmental concerns and energy security are important motivations for new transport systems. Sustainability issues may impose constraints on the use of alternative fuels or vehicle designs and understanding these issues will be necessary if a low carbon future transport system is to be achieved.

Meeting future goals for GHG emissions and energy security will mean displacing today's ICEVs, planes, trains, and ships with higher efficiency, lower emission models and ultimately adopting new, low- or zero- carbon fuels that can be produced cleanly and efficiently from diverse primary sources. There is considerable uncertainty in the various technology pathways, and further RD&D investment is needed for key technologies including batteries, fuel cells, hydrogen storage, and for RE and low carbon production methods for biofuels, hydrogen, and electricity. Given these uncertainties and the long timeline for change, it is important to maintain a portfolio approach that includes behavioural changes (to reduce VKT), more efficient vehicles, and a variety of low-carbon fuels. This approach will recognize that people ultimately make the vehicle purchase decisions, and that different technologies and fuel options will fit their various situations. Recent studies (IEA 2008; IEA 2009) see a major role for RE transport fuels in meeting societal goals, assuming that strict carbon limits are put in place.

8.3.2 Buildings and households

The buildings and household sector in 2007 accounted for ~116 EJ, or about 30 % of total global final energy demand. Around 40 EJ of this total was from combustion of traditional biomass for cooking and heating. By 2030, the total demand could rise to ~136 EJ (Fig. 8.2). GHG emissions from the building sector, including through electricity use, were about 8.6 Gt CO_2 in 2004 (IPCC, 2007) with scope for significant reduction potential[17] (Metz, Davidson et al. 2007; IEA 2009). The sector provides a variety of basic energy services to support the livelihoods and well-being of people living in both developed and developing countries including for:

- preparation of food for consumption and sale;
- refrigeration of food and other perishable items including medicines / vaccines;
- cooking – 95% of staple foods needing to be cooked (Practical Action, 2010);
- heating of building space in colder regions;
- heating of water for washing, distillation and desalination;
- cooling of building space, particularly in tropical regions;
- lighting for streets, commercial buildings, and households to allow night study;
- communications and entertainment including telephones, computers, TV, radio;
- mobility of people and transport of products to markets;
- social services including water pumping and purification, health treatment, and education; and
- industrial activities necessary for agriculture, agro-processing, industrial enterprises, manufacture of goods and provision of services.

Energy carriers including are converted into energy services in a variety of ways. Although it is possible to use different types of energy to provide the same service, it is also possible to select a vector for its specific characteristics that are most suitable to meet the specific requirements of the energy service to be provided (Table 8.6).

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[17] Full details of the potential for energy efficiency and RE in the building sector were provided in Chapter 6 of the IPCC 4th Assessment Report – Mitigation (Metz *et al*., 2007).

Table 8.6. Energy carriers and their suitability for providing basic energy needs.

	Solid fuels (wood, charcoal)	Liquid fuels	Gaseous fuels	Mechanical power	Electricity
Cooking	XXX	XX	XXX		XX
Space and water heating	XXX	XXX	XXX		XX
Space cooling					XXX
Lighting	X	XX	XX		XXX
Refrigeration	X	XX	XX		XXX
Communication/ entertainment					XXX
Mobility and transport	X	XXX	X	XX	X
Social services				XX	XXX
Productive uses	XX	XX	XX	XXX	XXX

X = possible but not usually preferable; XX = applicable but limited; XXX = most suitable

Energy for cooking, water heating and waste treatment is deemed to be a basic human requirement, although for many millions of people living in developing countries, these services are not always readily available. For residential and commercial buildings, energy carriers and service delivery systems vary depending on the local characteristics of a region and its wealth. Building owners and managers use energy to provide comfort for those working or living there through space heating, ventilation and cooling as well as for lighting, and powering appliances.

The present use of fossil fuels to provide heating and cooling can be replaced economically in many regions by modern biomass and enclosed stoves, ground source heat pumps, solar thermal and solar sorption systems (IEA 2007). The total global demand for RE heating (excluding traditional biomass) is around 3.5-4.5 EJ/year. Policies to encourage the greater deployment of RE heating/cooling systems are limited but several successful national and municipal approaches are in place (IEA 2007).

RE integration differs between commercial high-rise apartment buildings in mega-cities and small towns of mainly individual dwellings; between wealthy suburbs and poor urban areas; between established districts and new sub-divisions; and between farming and fishing communities in OECD countries and small village settlements in developing countries that have limited access to energy services. The following section covers these regional differences.

8.3.2.1 Urban settlements in developed countries

In OECD and other major economies, most urban buildings are connected to electricity, water, and sewage distribution schemes. Many have natural gas supplied for heating and cooking giving greater convenience for residents than using coal, biomass or oil-products to provide these services. RE resources are widespread but have low energy density by comparison with fossil fuels and RE conversion technologies can be comparatively expensive. Nevertheless, integration in buildings is expanding in order to improve residents' quality of life at the same time as realizing low carbon and secure energy supplies (IEA 2009). RE deployment in a building is often combined with the enhancement of energy efficiency as well as energy conservation via behavioural change.

8.3.2.1.1 Challenges caused by RE integration

Efforts to improve energy efficiency and utilize low carbon energy sources are largely dependent on the motivation of building owners and inhabitants. Institutional and financial measures such as energy auditing, labelling, subsidies, regulations, incentives and automatic billing systems can lead to increased deployment. The features and conditions of energy demand in an existing or new building differ with location and design. Effective and efficient methods and technical products are being developed to apply to buildings under a variety of situations.

The transition from a fossil-fuel based, centralized energy supply system into a more distributed system with increased RE (8.2.1.6) will need a drastic revision of how urban space has been traditionally planned and occupied. The required changes in land and resource use to better accommodate RE technologies in parallel with the existing energy supply is one of the major structural changes that will shape their integration.

The greater deployment of RE resources in an urban environment (IEA 2009) may require innovative use of roof and wall surfaces of city buildings. This will impact on the orientation and height of buildings to gain better access to solar radiation and wind resources without shading. Local seasonal storage of excess heat using ground source heat pumps, and access to surface ground water, may need to be considered. The opportunity is available for buildings to become energy suppliers rather than energy consumers. Building-integrated PV systems have experienced rapid growth reaching 20 GW capacity in 2009 (REN21 2006) but the present PV market of around US$(2005) 20 bn/yr could become constrained by lack of standardisation, lower production volumes and competition from PV panels when applied to buildings as retrofits (Lux 2009). Retrofits can now encompass roof-integrated systems that resemble traditional roof coverings.

Appliances in buildings could also contribute to maintaining the supply/demand balance of the energy system through demand response and energy storage (possibly including electric vehicles in future). This is an important spatial option for some cities and towns, possibly requiring adaptation of the local electricity (8.2.1) and/or heating/cooling distribution grid (8.2.2). Technological advances are required in order to speed up the integration of RE into the built environment including energy storage technologies, real time meters, demand-side management and more efficient systems that also have benefits for the power supply system. New RE technologies may need to be accompanied by innovative and progressive energy regulations and incentives to obtain their more rapid dissemination (IEA 2008). Several examples exist of successful government policies and entrepreneurial initiatives that can be replicated elsewhere.

Many buildings are leased to their occupiers, leading to the conundrum of owner/tenant benefits. Investing in energy efficiency or RE initiatives by the building owner usually benefits the tenants more than the investor, so that return on investment often has to be recouped through higher rents. Relatively high capital investments by building owners and long payback periods for technologies such as solar water heaters, or ground source heat pumps, can be a constraint, possibly overcome by government grants, utility leasing arrangements, or micro-financing schemes to access modern energy services.

8.3.2.1.2 Options to facilitate RE integration into urban supply systems

New building designs in both hot and cold regions have demonstrated that imported energy for cooling/heating can be minimised by careful design and the use of adequate insulation and thermal sinks. Building codes are steadily being improved to encourage the uptake of such technologies, and it is hoped that by around 2050, most new buildings will require little, if any, heating or cooling using imported energy.

Existing buildings can often be retrofitted to significantly reduce their energy demand for heating and cooling using energy efficient technologies such as triple glazing, cavity wall and ceiling insulation, shading, and white painted roofs. In OECD countries many building designs demonstrate these passive solar concepts well, but they remain a minority due to slow stock turnover. The lower the energy demand that the inhabitants of a building require to meet comfort standards as well as other energy services, then the more likely that RE can be employed to fully meet those demands.

Solar thermal and solar PV technologies can be integrated into building designs as components (such as roof tiles, wall facades, windows, balcony rails etc). Innovative architects are beginning to incorporate such concepts into their designs. Integration of PV panels into buildings during construction can replace the look and function of traditional building materials for roofs, windows overhangs, and walls, thereby improving the aesthetics and system reliability while reducing costs and utility transmission losses. Development of small wind turbines with low noise and little vibration can make roof-mounting more acceptable to building inhabitants and neighbours, though flickering may remain an issue in some situations.

Distributed CHP systems (biomass, solar thermal, geothermal, H_2 from electrolysis or fossil fuels) at medium and small scales (Liu and Riffat 2009), could be used on-site to produce sufficient heat and power to meet local demands with excess exported off-site to gain revenue (IEA 2009). CHP combustion/steam generation engines, gas turbines, and other conversion technologies are available at large (50 MW_e) and small (5 kW_e) scales with on-going research into fuel cells and micro-CHP systems (Leilei *et al*., 2009). [Authors: Source does not appear in reference list]

Greater integration of RE into the built environment is directly dependent on how urban planning, architectural design, engineering and a combination of technologies could be integrated. Tools and methods to assess and support strategic decisions for planning new building construction and retrofits are available (Doukas, Nychtis et al. 2008). For subsequent stages, other methods, including computer simulations, are necessary to project the outcomes of a strategy (Dimoudi and Kostarela 2008; Larsen, Filippin et al. 2008).

8.3.2.1.3 Efficiency and passive RE integration

Air conditioning is one of the largest energy uses in buildings, mainly for space heating in high latitudes and cooling in low latitudes. A well designed and insulated building requires little imported energy and various kinds of building materials and construction methods are available. To reduce heating demand these include vacuum insulation panels, multi-foil insulation, insulation paint, vacuum glazing, and triple glazed windows, and for cooling, automatic shading and electro-chromatic glazing systems. Substantial design progress has been made in high performance heat pump air conditioners utilising atmospheric or ground heat. For single-residential, multi-residential, or commercial air-tight buildings, high energy demands for forced ventilation can be reduced through appropriate selection and hybridization of PV generation, solar chimneys and wind cowls (Antvorskov 2007).

Improved efficiency appliances for lighting, cooking, water heating, high thermal insulation refrigeration, liquid crystal displays (LCD), stand-by power modes etc. continue to be sought by R&D, and many RE technologies are also under development for use in residential and commercial buildings (Fig. 8.29). Smart appliances that use low energy and operate automatically at off-peak times for use with future intelligent electricity networks (IEA 2009), are reaching the market.

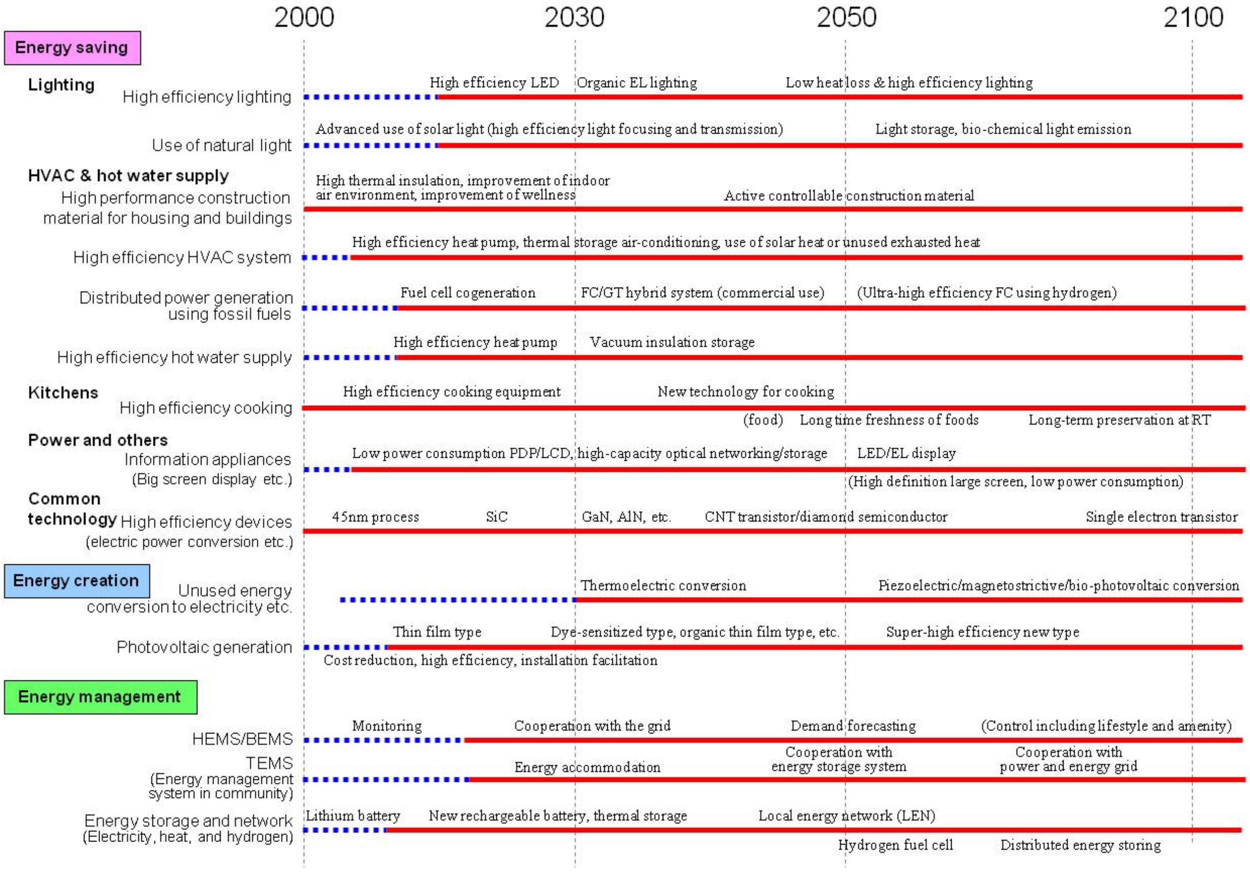


Figure 8.29: Technology development pathways for future energy efficiency and RE technologies for use in residential and commercial buildings (METI 2005).

8.3.2.1.4 Energy management technology

An energy manager of a building is usually responsible for multiple objectives including comfort, energy efficiency, environmental impacts and the integration of RE, all for minimal cost. In commercial buildings, various building energy management systems and controls have been developed to balance these multiple objectives (Dounis and Caraiscos 2009). Measuring and monitoring both energy use and the building environment are usually required (Wei, Yong et al. 2009). Monitoring techniques have been deployed in multi-family buildings with home energy management standard technologies produced to control and actuate appliances.

Advanced electricity meters, with bi-directional communication capability and related information infrastructure technology, are expected to be widely deployed to gain the benefits of demand response in combination with interfacing intelligent technology for appliances, distributed generation and energy storage (NETL 2008) (8.2.1.6).

8.3.2.1.5 Policies and regulations

Regardless of the type of RE technology, policies including building codes and minimum air emission standards are needed to help overcome barriers (including education and training of engineers, architects and installers), and to encourage rapid deployment in both new and existing buildings. Urban planning regulations may need modification to encourage rather than hinder deployment (IEA 2009). For example, regulations to protect the solar envelope for PV and solar thermal installations and prevent shading from newly planted trees and new building construction need to be developed, along with easing the process to obtain a resource or building consent within pre-determined guidelines.

8.3.2.1.6 Case studies

An analysis (WBCSD 2009) depicted the pathway for energy efficiency of single-family homes in France and an office building in Japan.

Single-family homes in France. Energy consumption is usually dominated by space heating being around two thirds of the total demand (Fig. 8.30). Solar PV and solar thermal were the major potential RE sources for these buildings and energy efficiency offers potential by reducing space heating needs through insulation, air tightness, improvements in domestic hot water and lighting.

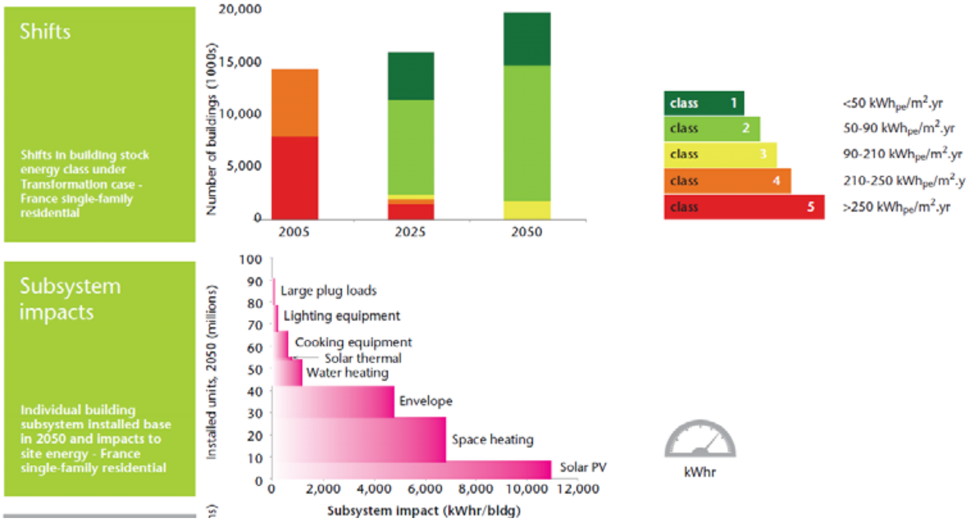


Figure 8.30: Possible trends in building stock energy classes from 2005 to 2050 and projected installations of energy saving technologies and integrated solar thermal and solar PV by 2050 for single-family homes in France (WBCSD 2009).

Office buildings in Japan: Heating and cooling equipment have the highest potential to reduce energy demand followed by lighting (Fig. 8.31). PV is the major RE source projected to be used in 2050, especially for low-rise buildings.

Figure 8.31: Possible trends in building stock energy classes from 2005 to 2050 and projected installations by 2050 of energy saving technologies and solar PV in office buildings in Japan (WBCSD 2009).

Distributed energy management technology for buildings is now under development, incorporating latest IT technologies to effectively control domestic peak demand and use energy storage equipment and DG systems in or around buildings (Cheung 2010). Buildings that have been passive energy consumers could become energy producers and building managers could become co-operators of an energy network (USDOE 2008).

Assuming low stock turnover of buildings of around 1% per year in developed countries, retrofitting of existing buildings will play a significant role for energy efficiency and RE integration (Ravetz 2008; Roberts 2008). Among many activities to pursue optimum retrofitting to gain 100% energy supply for heating, cooling & electricity, the "Renewable Energy House" in Bruxelles is a good example (8.2.5.5) (EREC 2008). Another example of retrofitting is residential buildings in China's northern region where exterior windows, roofs, and heating system were retrofitted and the importance of metering of energy use and management is based on actual data (Zhao, Zhu et al. 2009).

8.3.2.2 Urban settlements in developing countries

Urban energy consumption patterns of the more wealthy members of society in many developing countries resemble those of developed countries (8.3.2.1). For the urban poor, commercial energy sources rely mainly on traditional biomass, particularly that sourced from animal dung and vegetation located close to urban consumption centres. The inefficiency of the whole supply chain, together with indoor air pollution problems, affect a large proportion of the urban population, particularly the many women who still rely on fuelwood or charcoal for their basic cooking and heating needs. In sub-Saharan Africa and elsewhere, many urban areas continue to experience a transition from fuelwood to charcoal which is impacting negatively on deforestation, given the low energy conversion efficiency of traditional kilns used in the carbonization process.

In many urban areas of developing countries, including in China, solar water heaters are considered to be a good RE option. Large-scale implementation of solar water heating can benefit both the customer and the utility. For a utility that uses centralised load switching to manage electric water-heater load, the impact of solar water heaters is limited to energy savings. For utilities that do not, then the installation of a large number of solar water heaters may have the additional benefit of reducing peak demand on the grid. In high sunshine regions, maximum solar water-heater output corresponds with peak summer electrical demand for cooling, and there is a capacity benefit from load displacement of electric water heaters. Emission reductions can result, especially where the solar water heating displaces the marginal and most-polluting generating plant used to produce peak-load power. A market niche for solar water heaters remains, particularly in the service sector such as hotels and lodges as well as in middle and high income households. Regulations and incentives could be necessary to reach a critical mass in many regions and hence gain larger dissemination.

8.3.2.2.1 Challenges and options

The major challenge is to reverse inefficient biomass consumption pattern by providing access to modern energy services while increasing the share of sustainable RE sources. In some urban areas, grid electricity is available although often unreliable and limited to basic needs. It is unlikely that decentralized RE will secure significant penetration in the next two decades. The introduction of liquid or gaseous RE fuels to replace solid biomass for cooking could play a critical role whilst improving the health of millions of people. In some regions LPG has displaced charcoal, though this is a costly option for the majority of poor people and only a few countries have achieved significant penetration. LPG, if subsidised, can become a high burden on a state budget. Its use benefits mainly middle and high income people as well as businesses. Replacing LPG by DME (di-methyl ether) produced from biomass, shows some potential. The scale of biofuel production that would be needed to meet cooking fuel demand is less than that for meeting transport fuel demand (8.2.4; 8.3.1).

A further challenge is to ensure that biomass as used extensively for fuel by many urban and rural communities in developing countries is supplied from sustainably produced forests. Many land areas close to urban areas have already been depleted of trees. In Senegal as a result, charcoal for use in urban areas is supplied from forests in excess of 400 km away, leading not only to high prices but also to relatively high GHG emissions as a result of inefficient carbonisation technologies and road transport.

Biomass will probably remain a valuable fuel in many urban centres in poor developing countries. To ensure the sustainability of biomass resources, a holistic approach encompassing supply (plantations, natural forest management) and demand (fuel switching, efficient equipment such as improved stoves and kilns) is required (Fig. 8.32). This approach could be accompanied by fiscal policies (for instance differential taxation) to provide financial incentives for biomass only being supplied from sustainable sources.

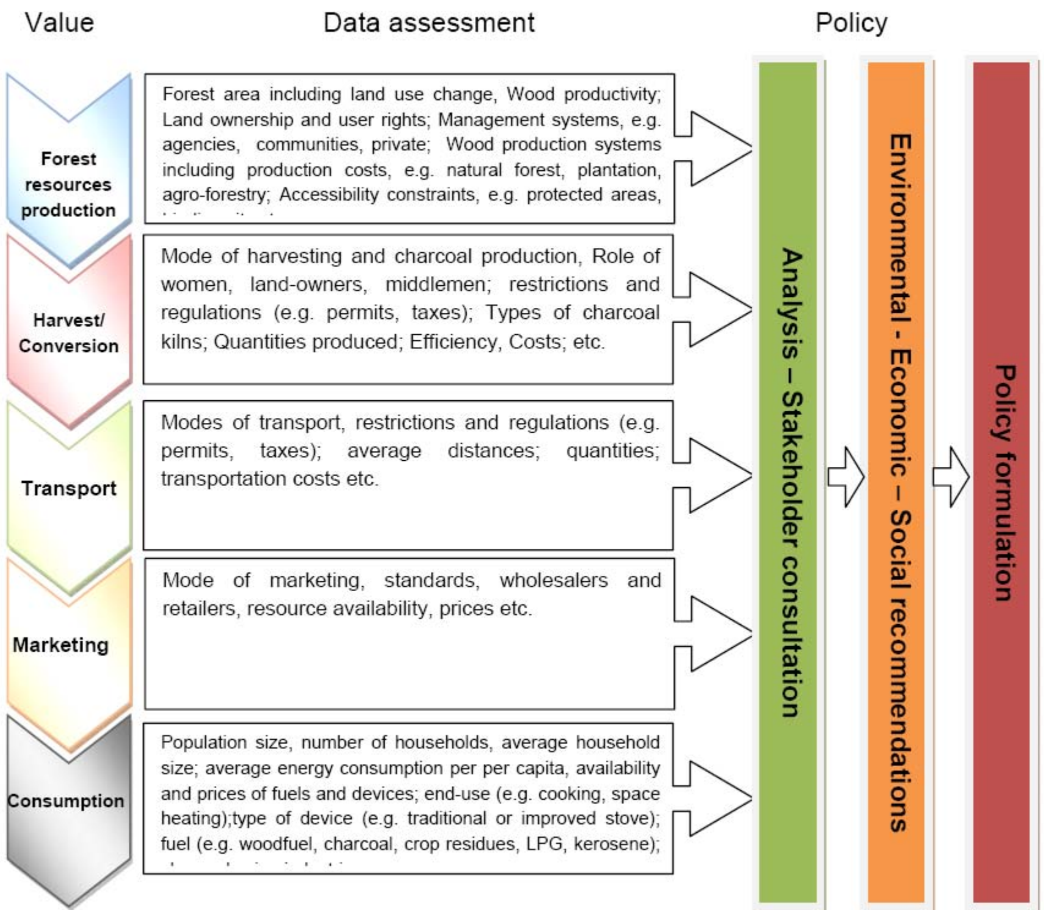
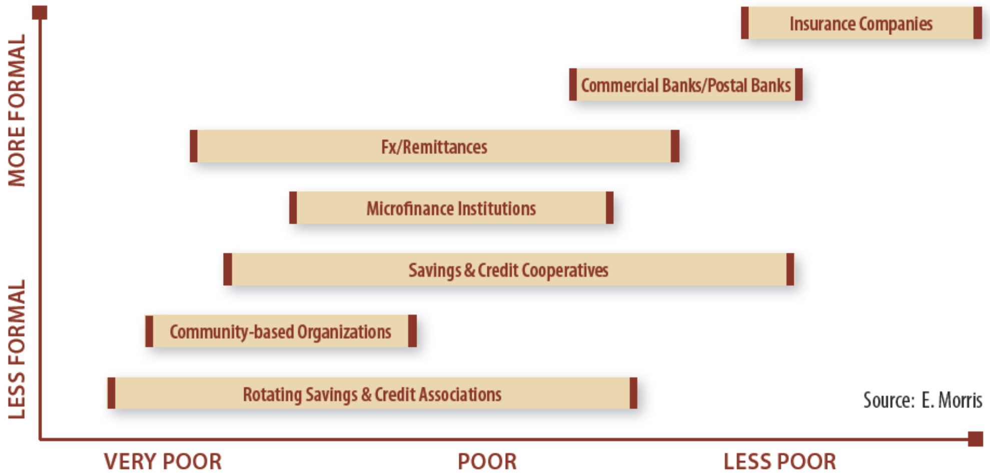


Figure 8.32: A holistic approach to sustainable RE supply using chain analysis of woody biomass supplied for energy purposes (Khennas, Sepp et al. 2009). [TSU: Figure will need to be redrawn to assure that all text is visible in data assessment boxes]

8.3.2.2.2 Case Studies

Peri-urban settlements in Brazil. The fast urbanization process in many developing countries has created peri-urban areas near to central metropolitan areas. In Brazil, all major cities and about one third of all municipalities have a large fraction of their population living in peri-urban areas that frequently lack proper services and basic urban waterworks, sanitation and electricity distribution infrastructure (IBGE 2008). Dwellings constructions are, for the most part, precarious, fragile and temporary and energy planning is complex. Where a distribution grid is available, it often does not comply with the standards of the utility, there being illegal connections and no meters. This can provide an opportunity to create new RE technologies. Depending on the type of settlement, a combination of small-scale energy technologies suitable for rural communities or urban dwellings could be employed where they can be financed (Fig. 8.33). These include treadle and wind pumps, solar pumps, improved stoves, biodiesel as a fuel for stationary engines, solar water heaters, wind turbines, biomass gasifiers and solar PV systems.



Source: E. Morris

Figure 8.33: Financing options to provide energy services for the poor (based on experience in Burkina Faso, Kenya, Nepal and Tanzania) (UNDP 2009).

Access to energy services is not necessarily the main problem of the majority of the urban and peri-urban poor, but rather the ability to afford the services. Therefore, greater penetration of RE technologies will need to be accompanied by comprehensive energy policies and tariffs so as to enable these households to make use of RE.

Access to modern energy services is a challenge for many local governments and energy utilities. Brazil's electricity utilities invest about US$(2005) 80M annually in low-income, energy efficiency programmes, about half of their compulsory investments in end-use programmes under current regulations. A number of complex issues still need to be tackled including enforcing legal regulations, developing more creative and technical solutions to treat theft and fraud in services, and the improving the economic situation of poor populations living in a peri-urban setting.

Low-income energy efficiency and solar water heating programmes have been promoted. A number of programmes have replaced inefficient light bulbs and refrigerators, improved local distribution networks and maintained individual connections (including re-wiring of domestic installations). Modern and state-of-the-art technologies are leap-frogging in some peri-urban districts, including remote metering, real-time demand monitoring of households, more efficient transformers, new cabling systems and improved materials (ICA 2009).

A pilot case study in one "favela" in São Paulo reported the reduction of household electricity consumption from 250 kWh/month to 151 kWh/month and an internal rate of return on investment of 276% with a payback of only 1.36 years. The financial analysis assumed a reduction in commercial and technical losses and increased revenues for the utility due to a reduction in arrears and non-payments (ICA 2009).

Multi-family housing in China. Over 90% of the population in Chinese urban areas live in multi-family apartment buildings. The major energy reduction potential is in space heating consumption, water heating and lighting (Fig 8.34). Solar thermal is the major RE source utilized. Sub-metering, apartment-level controls within the building, and billing of individual apartments are key to small-scale RE deployment possibilities.

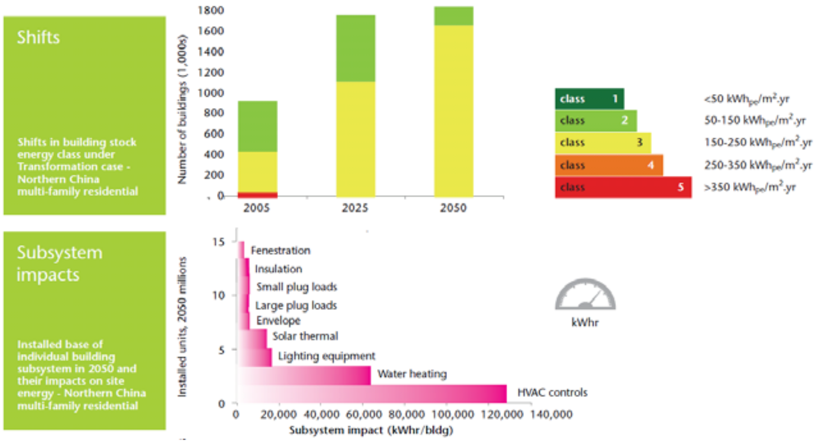


Figure 8.34: Possible trends in building stock energy classes from 2005 to 2050 and projected installations by 2050 of energy saving technologies and solar water heaters in multi-family houses in China (WBCSD 2009).

8.3.2.3 Rural settlements in developed countries

The energy consumption pattern in rural areas of developed countries does not differ a great deal from urban areas where good infrastructure exists. Modern forms of energy include electricity, natural gas, LPG and coal, however there is scope for more RE, particularly local, sustainably produced biomass for space heating.

8.3.2.3.1 Challenges of RE integration

Local RE sources can be captured to meet local energy demand but also any surplus energy can be exported and hence contribute to meeting the national demand. Finance and lack of awareness by landowners are among the key barriers to reaching this objective. Although financing might be available for some schemes (Fig. 8.33), obtaining up-front investment can be a hindrance to mobilising RE on a large scale. Institutional barriers, such as obtaining planning permission, often increase delays in implementing RE schemes, thus raising the transaction costs of integration.

8.3.2.3.2 Options to facilitate RE integration

Distribution companies with old, low voltage line networks near capacity can benefit from new distributed generation systems being installed near the demand to delay costly line-upgrading (see Case study, 8.3.4.5). Advanced bioenergy technologies for CHP systems can have a significant impact on the energy supply in countries such as Sweden and US where, as a result of increased biomass demand, the rate of afforestation has increased (Mabee and Saddler 2007). The following case study illustrates opportunities for RE deployment.

8.3.2.3.3 Case Study

Sustainable energy partnership and penetration of RE in rural England. The county of Cornwall, covering the rural peninsula in the south-west region of England, is pioneering partnerships for the delivery of energy initiatives. Because of its peripheral location, the region has limited access to natural gas pipelines but has sufficient solar, wind, marine, small hydro and biomass resources to meet the county’s energy demand. In 2004, the Cornwall Sustainable Energy Partnership (CSEP) published the UK’s first sub-regional sustainable energy strategy (EC 2004). The strategy’s 32 point action plan aimed to support the use of natural resources, deliver local, national and international RE targets, incorporate greater energy efficiency and RE in buildings, and reduce carbon emissions (CSEP 2004). The “Energy in Buildings” group of the CSEP is the lead delivery partnership for this local area agreement (LAA).

Two years after the CSEP began, the installed capacity of RE technologies in domestic and community buildings tripled as a result of 6-fold increase in the number of RE systems installed in domestic and community buildings throughout Cornwall. As part of the LAA delivery plan, CSEP provided free technical and funding advice to developers, architects, housing associations, community groups etc. It facilitated distributed micro-generation installations in a number of social and private sector housing developments. The strategy commits the partnership to doubling Cornwall’s current RE generating capacity to achieve a sub-regional target of at least 93 MW_e installed capacity by 2010.

8.3.2.4 Rural settlements in developing countries

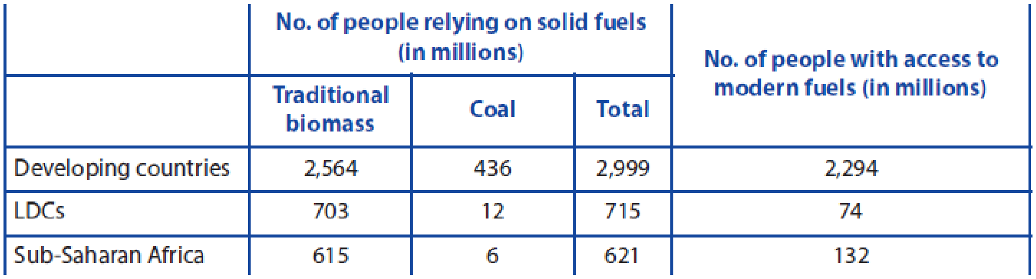
In several sub-Saharan Africa and many other developing countries, traditional biomass accounts for more than 75 % of primary energy. Rural households rely mainly on non-commercial crop residues, fuelwood and animal dung for their basic energy needs for cooking and heating. Unlike urban areas, the biomass can be collected locally, generally by women, from nearby woodlands and savannah lands. Although the daily time devoted to this chore has been increasing in some regions as the local biomass resources become diminished in a non-sustainable fashion, the illusion of a free commodity coupled with severe poverty makes it difficult to substitute firewood with modern energy forms or even to improve energy efficiency for cooking. Providing local plantations to be harvested sustainably (instead of from scavenging) is one solution, but not always easy to accomplish due to land ownership complexities and other social issues.

In 2005, 570 million cooking stoves used in rural areas had replaced very inefficient open fires, of which 220 million were improved stove designs (REN21 2006). Lighting demands can be met by kerosene lamps, torches and candles, all of which are expensive options. Only a tiny fraction of rural households in developing countries have access to modern energy services which is a major constraint to eradicating poverty and improving health, education, and social and economic development.

8.3.2.4.1 Challenges of RE integration

Around 2.6 billion people depend on traditional biomass (Table 8.7) including 89% of the population of sub-Saharan Africa. Around 1.6 billion people, mainly in rural areas, do not have access to electricity (Vijay, McDade et al. 2005). Resulting environmental impacts and future supply strategies vary depending on whether a region is rural, urban or peri-urban, and the key challenge for members of rural communities is to move up the energy ladder (Fig. 8.35)

Table 8.7: Number of people relying on solid and modern fuels (e.g. LPG, kerosene, biogas) for cooking in developing countries, least developed countries (LDCs) and sub-Saharan Africa (SSA) (UNDP 2009).



	No. of people relying on solid fuels (in millions)			No. of people with access to modern fuels (in millions)
	Traditional biomass	Coal	Total	
Developing countries	2,564	436	2,999	2,294
LDCs	703	12	715	74
Sub-Saharan Africa	615	6	621	132

Note: Based on UNDP classification of DC and LDCs, there are 50 LDCs and 45 SSA countries with 31 countries belonging to both categories.

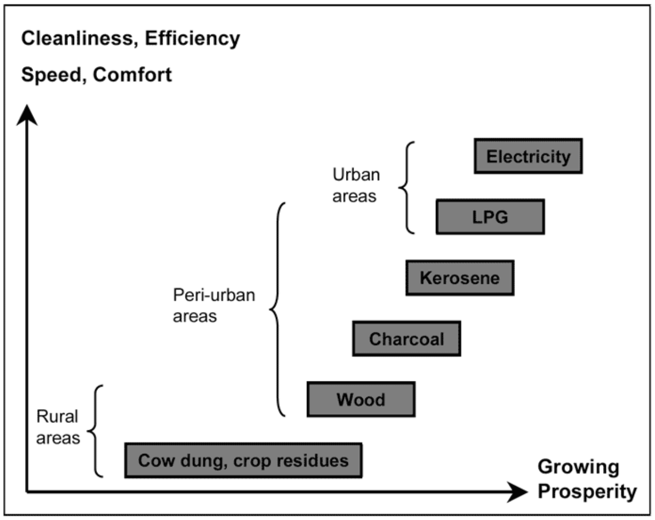


Figure 8.35: The “energy ladder” indicates how growing prosperity results from improved energy quality and energy availability (Mahamane, Lawali et al. 2009).

Some energy-poor may obtain electricity from the grid in the next few decades in some regions as extension of the distribution network reaches more peri-urban people currently without access to modern energy services. Obtaining sufficient funding for purchasing the power could be challenging, even if energy consumption remains limited to basic needs such as lighting, radio, and mobile phone recharging. If innovative finance mechanisms can be put in place (UNDP 2009), then the energy poor may better utilize local RE technologies as the least cost option available.

8.3.2.4.2 Options to facilitate RE integration

Although rural income is generally lower than urban income, there could be a market for RE for wealthier rural people, entrepreneurs and social institutions (churches, mosques). For example solar PV, micro-hydro power, and biogas could be developed locally on a sustainable basis to service rural communities, institutions and businesses who can afford to invest in such appropriate technologies. For the majority of rural people however, innovative and affordable delivery mechanisms need to be developed such as concessions coupled with subsidies and public private partnerships to increase energy access.

8.3.2.4.3 Case Study

RE in the Democratic Republic of Congo. The Congo Basin has the second largest tropical rainforest area in the world after the Amazon. The level of deforestation in absolute values is particularly high, particularly in the Democratic Republic of Congo (DRC) which is the largest and most populated country of the Congo Basin (Table 8.8). Paradoxically, despite the large hydro potential in the region, the rural electrification rate is extremely low at less than 1% of population per year (Fig. 8.36). The prospects to develop the micro- and mini- hydro potential of the region are therefore high which would dramatically increase the rural electrification rate and ultimately improve the livelihood of the energy poor rural people. In DR Congo alone, some 325 potential hydro schemes have been identified for which preliminary data have been gathered (Khennas, Sepp et al. 2009). The implementation of such a programme would dramatically increase the supply of RE for rural people to meet their needs for basic energy services and could also contribute to limiting deforestation around the villages.

Table 8.8: Annual deforestation rates in the Congo Basin countries between 1990 and 2000.

	Forest area[1] **(*1000 ha)**	**Gross deforestation**[2] **(% /year)**	**Net deforestation**[2] **(% /year)**
Cameroon	19 639	0.14	0.14
Equatorial Guinea	1 900	0.10	Not available
Gabon	22 069	0.09	0.09
Central African Republic	6 250	0.19	0.06
Republic of the Congo	22 263	0.07	0.02
DR Congo	108 359	0.21	0.20
Total Congo Basin	**180 480**	**0.19**	**0.10**

(1)(CBFP 2006) (2)(de Wasseige, Devers et al. 2009)

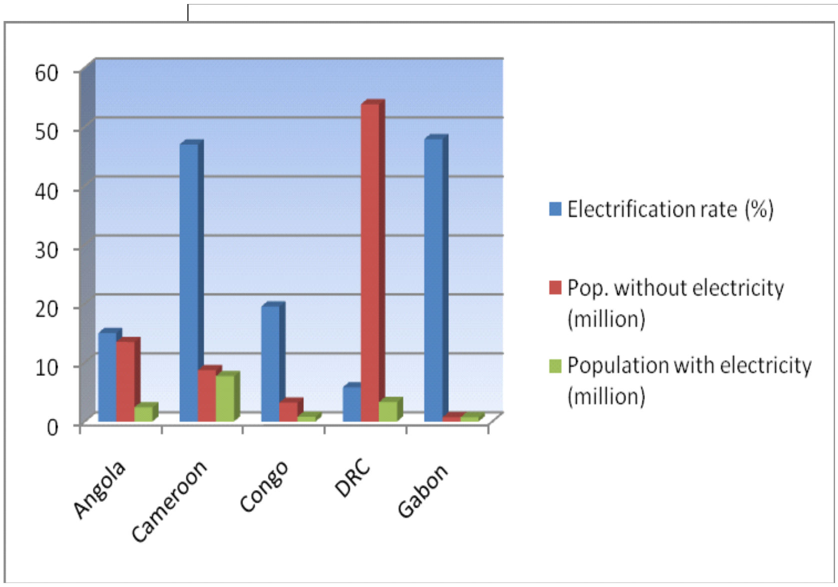


Figure 8.36: Electricity access in selected countries of the Congo Basin in 2005 (IEA 2006).

8.3.3 Industry

8.3.3.1 Introduction

Manufacturing industries account for about one-third of global energy use although the share differs markedly between individual countries. The industrial sector is highly diverse, ranging from very large, energy-intensive basic material industries to small and medium sized enterprises with light manufacturing. Perhaps 85% of industrial sector energy use is by energy-intensive industries: iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, minerals, and pulp and paper (Bernstein, Roy et al. 2007). The production of these industrial goods has grown strongly in the past 30-40 years and is projected to continue growing.

The sources of industry CO_2 emissions are direct and indirect use of fossil fuels, non-energy uses of fossil fuels in chemicals processing and production, and non-fossil sources such as CO_2 from calcium carbonate (CaCO3) in cement manufacturing. In most countries CO_2 accounts for more than 90% of industrial GHG emissions (Metz, Davidson et al. 2007). Direct and indirect CO_2 emissions in 2006 were 7.2 and 3.4 Gt respectively, together being equivalent to almost 40% of world energy and process CO_2 emissions (IEA 2009).

Carbon dioxide emissions from industry can be reduced by:

- energy efficiency measures to reduce internal energy use and, in some cases, make energy sources generated on-site available for sale (as waste heat, electricity and fuels);
- materials recycling to eliminate the energy-intensive primary conversion steps for many materials;
- RE integration and feedstock substitution to reduce the use of fossil fuels; and
- CCS of emissions from both fossil and biomass fuels.

All these measures are relevant for the issue of integrating RE into present and future energy systems. In addition, industry can provide demand-response facilities that are likely to achieve greater prominence in future electricity systems with more variable supply. The main opportunities for RE integration in industry include:

- Direct use of biomass derived fuels and residues for on-site biofuels, heat and CHP production and use (Ch. 2);
- Indirect use of RE through increased use of RE-based electricity, including electro-thermal processes;
- Indirect use of RE through other purchased RE-based energy carriers, e.g., liquid fuels, biogas, heat and hydrogen (section 8.2.3);
- Direct use of solar thermal energy for process heat and steam demands (Ch 3);
- Direct use of geothermal for process heat and steam demands (Ch 4).

Other RE sources may also find industrial applications (e.g., ocean energy for desalination, Ch 6). There are no severe technical limits to the increased direct and indirect use of RE in industry in the future. But integration in the short term may be limited by factors such as space constraints or demands for high reliability and continuous operation.

The current direct use of RE in industry is dominated by biomass in the pulp and paper, sugar and ethanol industries where biomass by-products are important sources of co-generated heat and electricity mainly used for the process. Biomass is also an important fuel for many SMEs such as brick-making, notably in developing countries. There is a growing interest in utilising waste and by-products for energy in, for example, the food industry through anaerobic digestion for biogas production. Waste and wastewater policies are important drivers for biogas production (Lantz, Svensson et al. 2007). Thus, industry is not only a potential user of RE but also a potential supplier of RE as a co-product. With the exception of biomass based industries the literature on RE in industry is relatively limited compared to the literature on RE in other sectors.

8.3.3.2 Energy-intensive industries

The largest contributions of CO_2 emissions in 2006 came from iron and steel (29%), cement (25%) and chemicals and petrochemicals (17%) (IEA 2009). The pulp and paper industry accounted for only about 2% of industrial CO_2 emissions but uses large amounts of biomass for process energy.

Iron and steel. Production of iron and steel involves ore preparation, coke making, and iron making in blast furnaces and basic oxygen furnaces to reduce the iron ore to iron. Primary energy inputs are 13 to 14 GJ/t from coal. Natural gas for direct reduction of iron-ore is also an established technology. Using electric-arc furnaces to recycle scrap steel, these energy-intensive steps can be by-passed and primary energy use reduced to around 4 - 6 GJ/t. However, the amount of scrap steel is limited and the increasing demand for primary steel is mainly met from iron ore.

Biomass, in the form of charcoal, was for a long time the main energy source for the iron and steel industry until coal and coke took over in the 1800s. During the production of charcoal, roughly one third of the wood energy content is converted to charcoal, the rest being released as gases but higher efficiencies are attainable (Rossilo-Calle, Bajay et al. 2000). Charcoal can provide the reducing agent in the production of iron in blast furnaces but coke has the advantage of higher heating value, purity and mechanical strength. Present day steel mills mostly rely entirely on fossil fuels and electricity and charcoal has not been able to compete, the exception being a few blast furnaces in Brazil.

Options for increasing the use of RE in the iron and steel industry in the near term include switching to renewable electricity in electric-arc furnaces and substituting coal and coke with charcoal, subject to resource and sustainability constraints. Switching to renewable methane is also an option. Research on electricity and hydrogen-based processes for reducing iron shows potential in the long term but CCS linked with coke combustion may be a less expensive option.

Cement. Production of cement involves extraction and grinding of limestone and heating to temperatures well above 950°C. Decomposition of calcium carbonate into calcium oxide takes place in a rotary kiln, driving off CO_2 in the process of producing the cement clinker. CO_2 emissions from this reaction account for slightly more than half of the total direct emissions with the remainder coming from combustion of fossil fuels. Hence, even a complete switch to RE fuels would reduce emissions by less than half.

The cement process is not particularly sensitive to the type of fuel but sufficiently high flame-temperatures are needed to heat the materials. Different types of waste, including used tyres, wood and plastics are already co-combusted in cement kilns. A variety of biomass-derived fuels can be used to displace fossil fuels. Large reductions of CO_2 emissions from carbonate-based feedstock are not possible without CCS, but emissions could also be reduced by using non-carbonate based feedstock (Phair 2006).

Chemicals and petrochemicals. This sector is large and highly diverse. High volume chemical manufacture of olefins and aromatics, methanol, and ammonia, account for more than 70% of total energy use in this sector (IEA 2008). The main feedstocks are oil, natural gas and coal, for providing the building blocks of products as well as for energy (Ren and Patel 2009). Chemicals such as ethanol and methanol may be considered both as fuels and as platform chemicals for products.

Steam-cracking is a key process step in the production of olefins and aromatics and various biomass fuels and waste could be used for steam production. Methanol production is mostly based on natural gas but it can also be produced from biomass or by reacting CO_2 with hydrogen of renewable origin.

The potential for shifting to renewable feedstocks in the chemicals sector is large (Hatti-Kaul, Törnvall et al. 2007). Many of the first man-made chemicals were derived from biomass through, for example, using ethanol as a platform chemical, before the shift was made to petrochemistry. A shift back to bio-based chemicals involves four principal approaches:

- Feedstock can be converted using industrial biotechnology processes such as fermentation or enzymatic conversions;
- Thermo-chemical conversion of biomass for the production of a range of chemicals, including methanol;
- Naturally occurring polymers and other compounds can be extracted by various means;
- Green biotechnology and plant breeding can be used to modify crops in non-food production.

Ammonia production in the fertilizer industry is an energy-intensive process which involves reacting hydrogen and nitrogen at high pressure. The energy embedded in fertilizer consumption represents about 1% of global energy demand (Ramirez and Worrell 2006). The nitrogen is obtained from air and the source of hydrogen is typically natural gas but also coal gasification, refinery gases and heavy oil products. Ammonia production gives a CO_2-rich stream and lends itself to CCS. Hydrogen from RE sources could also be used for the reaction and other nitrogen fixation processes are possible, including biological nitrogen fixation.

Forestry. The forest industry, including harvesting operations, saw mills, pulp and paper mills, and wood processing industries, handles large amounts of biomass. Residues and by-products to provide energy for internal use as well as for export are occurring all along the value chain. The internal use of biomass energy as a by-product means that the CO_2 intensity of the energy intensive pulp and paper industry is relatively low.

There are many different pulping processes but the two main routes are mechanical and chemical. With electricity-intensive mechanical pulping, wood chips are processed in large grinders and nearly all the wood ends up in the pulp which is used for paper such as newsprint. Heat is recovered from the mechanical pulping process and the steam produced is used for drying the paper and other processes. Chemical pulping is used to produce stronger high quality fibres and involves dissolving the lignin in a chemical cooking process. About half of the wood ends up in the spent pulping liquor that is concentrated in evaporators. The resulting black liquor is combusted in chemical recovery boilers and the bark component can also be combusted in separate boilers. The high pressure steam produced is used for CHP generation, enough to meet all the steam and electricity needs of a modern pulp mill.

Continuous incremental improvements in energy end-use efficiency, higher steam pressure in boilers, condensing steam turbines, etc., are reducing the need for purchased energy in the pulp and paper industry and can free up a portion of fuels, heat and electricity to be sold as co-products (Axegård, Backlund et al. 2002). Changing from the traditional recovery boiler to black liquor gasification in chemical pulping would increase the efficiency of energy recovery and facilitate higher electricity-to-heat ratios in the CHP system or the use of syngas for fuels production (see Case studies below) The main options for direct integration of RE is to replace fossil fuels in boilers, produce biogas from wastewater with high organic content, and switch from oil and gas to biomass, for example by using bark powder in lime kilns that produce calcium oxide for the preparation of pulping liquor.

Overall, possible pathways for increased use of RE vary between different industrial sub-sectors. Biomass can be co-fired with, or completely replace, fossil fuels in boilers, kilns and furnaces and there are alternatives for replacing petro-chemicals through switching to bio-based chemicals and materials. However, due to the scale of operations, access to sufficient volumes of biomass may be a constraint. Direct use of solar technologies is constrained for the same reason. For many energy-intensive processes an important future option is indirect integration of RE through switching to electricity and hydrogen. Electricity is also the main energy input for producing aluminium using the electro-chemical Hall-Héroult process. Assuming that CCS becomes an important element in future energy systems this will also be an option for energy-intensive industries, irrespective of whether the fuels used are of fossil or renewable origin.

The broad range of options for producing carbon neutral electricity and its versatility of use implies that electro-thermal processes could become more important in the future for replacing fuels in low (<200°C) and medium (200-400°C) temperature processes including drying, heating, curing, and melting. Plasma technologies can deliver heat at several thousand degrees Celsius and replace fuels in high temperature applications. Electro-thermal processes include heat pumps, electric boilers, electric ovens, resistive heating, electric arcs, plasma, induction, radio frequency and micro-waves, infrared and ultraviolet radiation, laser and electron beams (EPRI 2009). These technologies are presently used where they offer distinct advantages (such as primary energy savings, higher productivity or product quality), or where there are no viable alternatives (such as for electric-arc furnaces and aluminium smelters). Deployment has been limited since direct combustion of fossil fuels is generally less expensive than electricity. However, relative prices may change considerably under climate policies placing a value on carbon emissions.

Energy-intensive industries are typically capital intensive and the resulting long capital asset cycles constitute one of the main transition issues in this sector. Cyclical markets and periods of low profit margins are common in energy-intensive industries, and management focus is usually on cutting costs and sweating assets rather than on making investments and taking risks with new technologies. In existing plants, retrofit options may be constrained by, e.g., space limitations, risk aversion, and reliability requirements. Green-field investments mainly take place in developing countries where enabling energy and climate policies are less common than in developed countries. However, energy-intensive industries are also generally given favourable treatment in developed countries that have ambitious climate policies since they are subject to international competition and resulting risks of carbon leakage. Exemptions from energy and carbon tax, or free allocation of emission permits in trading schemes, are prevalent. But industries using biomass, such as the pulp and paper industry, can also benefit from and respond to RE policy (Ericsson, Nilsson et al. 2010). Sectoral approaches are considered in international climate policy in order to reduce carbon leakage risks and facilitate technology transfer and financing of mitigation measures (Schmidt, Helme et al. 2008).

8.3.3.2.1 Case studies

Black liquor gasification for bio-DME production. Black liquor gasification as an alternative to chemical recovery boilers is a technology that has been subject to R&D for more than 20 years and has also been demonstrated in a few pilot plants. The syngas produced (mainly CO and H_2) can be used with high efficiency in combined cycles for CHP or for the production of biofuels via, for example, the Fischer-Tropsch process (section 8.2.4). A pilot plant, the first one with pressurised gasification, for producing DME (di-methyl ether) is expected to begin production in Piteå, Sweden, in August 2010 with a capacity of about 4t/day. The plant, with financial support from the Swedish Government and the European Commission, involves companies Chemrec, Haldor Topsoe, Volvo, Preem, Total, Delphi and ETC. Compared to gasification of solid biomass, one advantage of black liquor is that it is easier to feed to a pressurised gasifier. Depending on the overall plant energy balance and layout there are often process integration advantages and potential for significant increases in energy efficiency. Energy which is tapped off for liquid or gaseous biofuels production (including DME) can be compensated for by using lower quality biomass for meeting pulp and paper process energy demands. In addition to DME production, the project also involves four filling stations and 14 DME trucks to study the viability of bio-DME as a fuel for heavy trucks.

Demand response in industry Industrial peak load shifting as a form of load management is an important measure to facilitate a greater uptake of variable RE generation in power systems (section 8.2.1). It can also reduce the need for high marginal cost generation, offer low cost system balancing and decrease grid reinforcement investment. The concept is already widely used to secure enough reserve- and peaking-capacity in many countries and is expected to become more important in the future. Existing programmes have mainly focused on industrial users that can shed relatively large loads through rescheduling, machinery interruption, thermal energy storage, cool stores, reducing demand response times, interruptible electric boilers, etc. Typically, industries are contracted to reduce or shut down load, sometimes remotely by the transmission system operator, according to pre-defined rules and against various means of financial compensation. For industry, reduced production and risks of process equipment failure associated with demand response are important considerations. Estimates of the potential depend on the level of industrial manageable power demand. According to one study the potential for demand response in the energy-intensive industries of Finland is 1280 MW, equivalent to 9% of total peak demand (Torriti, Hassan et al. 2010).

8.3.3.3 Other non-energy intensive industry

Non-energy intensive industries, although numerous, account for a smaller share of total energy use than energy-intensive industries but, are more flexible and offer greater opportunities for the integration of RE. They include food processing, textiles, light manufacturing of appliances and electronics, automotive assembly plants, wood processing, etc. Much of the energy demand in these industries is for installations similar to energy use in commercial buildings such as lighting, space heating, cooling and ventilation and office equipment. Most industrial heating and cooling demands are for moderate temperature ranges which facilitate the application of solar thermal energy, geothermal energy and solar-powered cooling systems with absorption chillers (IEA 2007; Schnitzer, Brunner et al. 2007). Solar thermal collector capacity in operation world wide in 2007 was almost 150 GW but less than 1% is in industrial applications (IEA-SHC 2010).

Process energy use is typically for low and medium temperature heating, cooling, washing, cooking pumping and air-handling, coating, drying and dehydration, curing, grinding, preheating, concentration, pasteurization and sterilization, and some chemical reactions. In addition, a range of mechanical operations use electric motors and compressed air to power tools and other equipment. Plants range in size from very small enterprises to large-scale assembly plants and sugar mills.

Many companies use hot water and steam for processes at temperatures between 50 and 120°C. When fossil fuels are used, installations that provide the heat are mostly run at temperatures between 120 and 180°C to enable the use of smaller heat exchangers and heating networks, since heat exchanger areas can be smaller with higher temperatures in process heat supply. Solar energy will therefore possibly focus more on engineering designs for operating at lower temperatures in order to optimise the whole system. For temperatures < 80°C, thermal collectors are on the market, but there is limited experience for applications that require temperatures up to 250°C (Schnitzer, Brunner et al. 2007). Such higher temperatures are possible using heat pumps or, in appropriate areas, concentrating solar thermal systems

Industrial electro-technologies can save primary energy by using electricity. Industrial CO_2 emissions can be reduced even if there are no primary energy savings, assuming electricity from RE resources replaces or saves fossil fuel-based thermal generation. Examples include freeze concentration instead of the thermal process of evaporation; dielectric heating (radio frequency and microwave heating) for drying; polymerisation; and powder coatings with infra-red ovens for curing instead of solvent-based coatings and conventional convection ovens (Eurelectric 2004). Other advantages include quick process start up, better process control, and higher productivity (EPRI 2009). The conventional wisdom that high quality (high exergy) electricity should not be used for low quality (low exergy) thermal applications may be challenged in a future decarbonised electricity system.

RE is most widely used in the food and fibre processing industries where on-site biomass residues are commonly used to meet internal energy needs, exported for use elsewhere, or constitute a waste disposal problem. Bio-based industries often provide opportunity for utilising residues that are normally left after harvest of the feedstock or generated on-site during processing. For cane-based sugar and ethanol production, the mills are typically self-sufficient or net sellers of energy from using the waste bagasse as fuel. Historically bagasse (the fibre remaining after crushing sugar cane for juice extraction), was combusted inefficiently to dispose of it whilst producing just enough heat and power for use on-site. For ethanol plants in Brazil the surplus electricity sold to the grid is expected to increase from about 9 to 135 kWh/t of cane between 2005/2006 and 2020 as a result of increasing steam pressure and higher rates of residue recovery (Macedo, Seabra et al. 2008).

In other food and fibre processing industries, wastewater with high organic content could be used for biogas production but currently is poorly utilized. In many developing countries, substantial amounts of crop residues in the form of husks, straw and shells from nuts, coffee, coconuts, rice, etc. can be used for heat and power generation. These residues are low cost and often used as fuel to supply heat for local industries together with fuelwood and charcoal. In developed countries, waste policies are an important factor driving the increased utilisation of biomass residues for energy.

Bio-based industries such as pulp and paper and the sugar/ethanol industries, as well as other process industries, generate waste heat that can be used in other industries and in district heating systems. Industrial ecology and symbiosis are relatively new concepts used to denote such inter-firm exchanges of energy, water, by-products etc. although these are not new phenomena. Greenhouses and fish-farming are also potential users of low-grade heat. An inventory of the Swedish forest industry found several examples of such inter-firm exchanges, but typically between different entities within the same company group (Wolf and Petersson 2007). The potential for increased indirect use of RE in such innovative way is difficult to estimate.

Dehydration of agricultural and other products is an important application of solar energy. In many developing countries the traditional method of dehydration in open air may result in food contamination, nutritional deterioration and large product losses. Solar dryer technologies that improve product quality and reduce drying times have been demonstrated. Examples include a solar tunnel dryer for hot chilli (Hossain and Bala 2007) and a solar dryer with thermal storage and biomass backup heater for pineapple (Madhlopa and Ngwalo 2007).

Geothermal energy could meet many process heat demands in industry at temperatures, or elevated by heat pumps to higher temperatures. Almost 500 MW of geothermal capacity, equivalent to about 4 % of worldwide direct applications of geothermal energy, is currently used for industrial process heat (Lund 2005). Current utilisation is only about 10 PJ with applications in dairies, laundries, leather tanning, beverages, and a paper mill in New Zealand. The potential is very large (see Chapter 4) and high capacity factors relative to solar thermal energy make it an attractive alternative for industry.

The potential for increasing the direct use of RE in industry is poorly understood due to the complexity and diversity of industry, and varying geographical and climatic conditions. Aggregate mitigation cost estimates cannot be made for similar reasons. Improved utilisation of processing residues in biomass-based industries and substituting for fossil fuels offer near-term opportunities. Solar thermal technologies are promising but further development of collectors, thermal storage, back-up systems and process adaptation and integration is needed. Increased use of energy carriers such as electricity and natural gas, that are clean and convenient at the point of end-use, is a general trend in industry. Indirect integration using electricity generated from RE sources, and facilitated through electro-technologies, may therefore have a large impact in the near and long-term. Direct use of RE in industry has difficulty competing at present due to the relatively low fossil fuel prices and low- or zero-energy and carbon taxes for industry. RE support policies in different countries tend to focus more on the energy, transport and building sectors than on industry and consequently potentials are relatively un-charted.

8.3.3.3.1 Case studies

Sugar industry and CHP. Limited grid access and low prices offered by monopoly-buyers of electricity and independent power producers have provided disincentives for many industries to increase overall energy efficiency and electricity-to-heat ratios in CHP production. Process electricity consumption in sugar and sugar/ethanol mills for example is typically in the range of 20-30/ kWh per tonne of fresh cane. Most mills have been designed to be self-sufficient in heat and electricity using mainly bagasse as a fuel in low pressure boilers. With high pressure boilers and condensing extraction steam turbines, more than 100 kWh/t can be produced for export. However sugar/ethanol mills provide opportunity for integrating a much higher level of biomass for energy in industry. The sugarcane tops and leaves are normally burned before harvest or left in the field after harvest. These could also be collected and brought to the mill to increase the potential export of electricity to more than 150 kWh/t. This could be further increased to over 300 kWh/t using gasification technology and combined cycles or supercritical steam cycles (Larson et al., 2001). Integrating the utilisation of biomass residues with sugar/ethanol mills and feedstock logistics offer cost and other advantages over separate handling and conversion of the residues.

Solar industrial process heat for industry. There is good potential to use solar heat for industrial processes. In 2003, the net industrial heat demand in Europe was estimated to be 8.7 EJ and the electricity demand was 4.4 EJ (Werner 2006). Heat demands were estimated in 2003 at low, medium and high temperature levels for several industries in EU 25 plus four accession countries, and three European Free Trade Association countries (Fig. 8.37). (The figure was created from German industry experiences that were applied to the IEA database for the target area). Industrial process heat accounted for around 28% of total primary energy consumption with more than half of this demand for temperatures below 400°C. This could be a suitable application for solar thermal energy (Vannoni, Battisti et al. 2008).

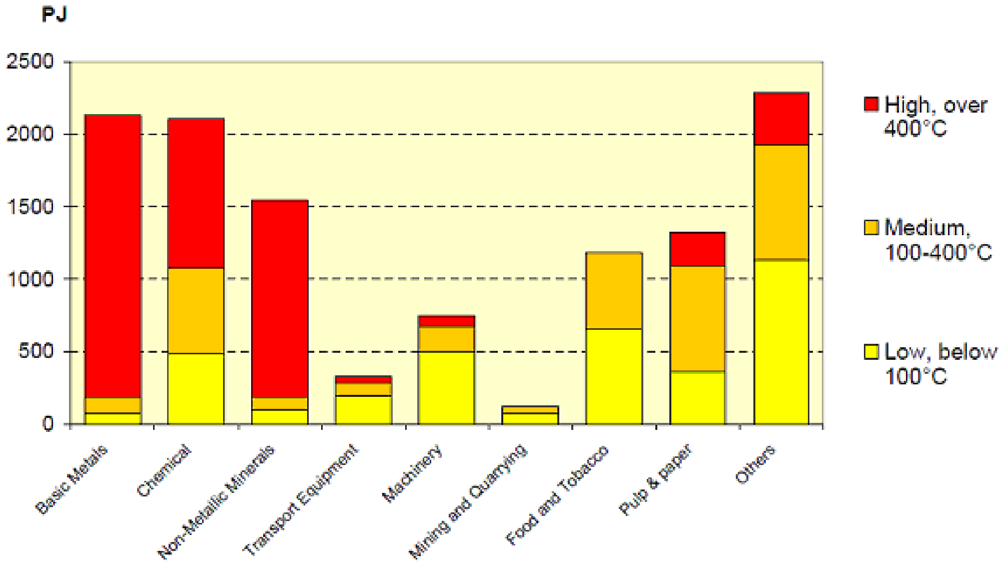


Figure 8.37: Industrial heat demands by temperature quality and by manufacturing sector for 32 European countries (Werner 2006).

Solar thermal energy technologies can be used to supply industrial heat including concentrating solar thermal systems that can produce steam directly in the collector. A pilot plant installed in Ennepetal, Germany in February 2007, the P3 project, aims to demonstrate direct steam generation in small parabolic trough collectors for industrial applications (Hennecke, Hirsch et al. 2008). The principal options for the integration of solar steam (Fig. 8.38) are:

- solar augmentation of the drying process;
- direct solar steam supply to individual consumers in the new production line; and
- solar steam integration into the existing steam distribution network. In this configuration the solar steam can feed directly into the production line by means of an over-pressure valve (>4 bar). The feed water to the solar steam generator is provided from the industrial steam system. Condensate from the solar system can be returned by the condensate line of the existing system. The feed water pump for the solar field is controlled by temperature measurement in the steam drum that is operated at a constant pressure of about 4.3 bar.

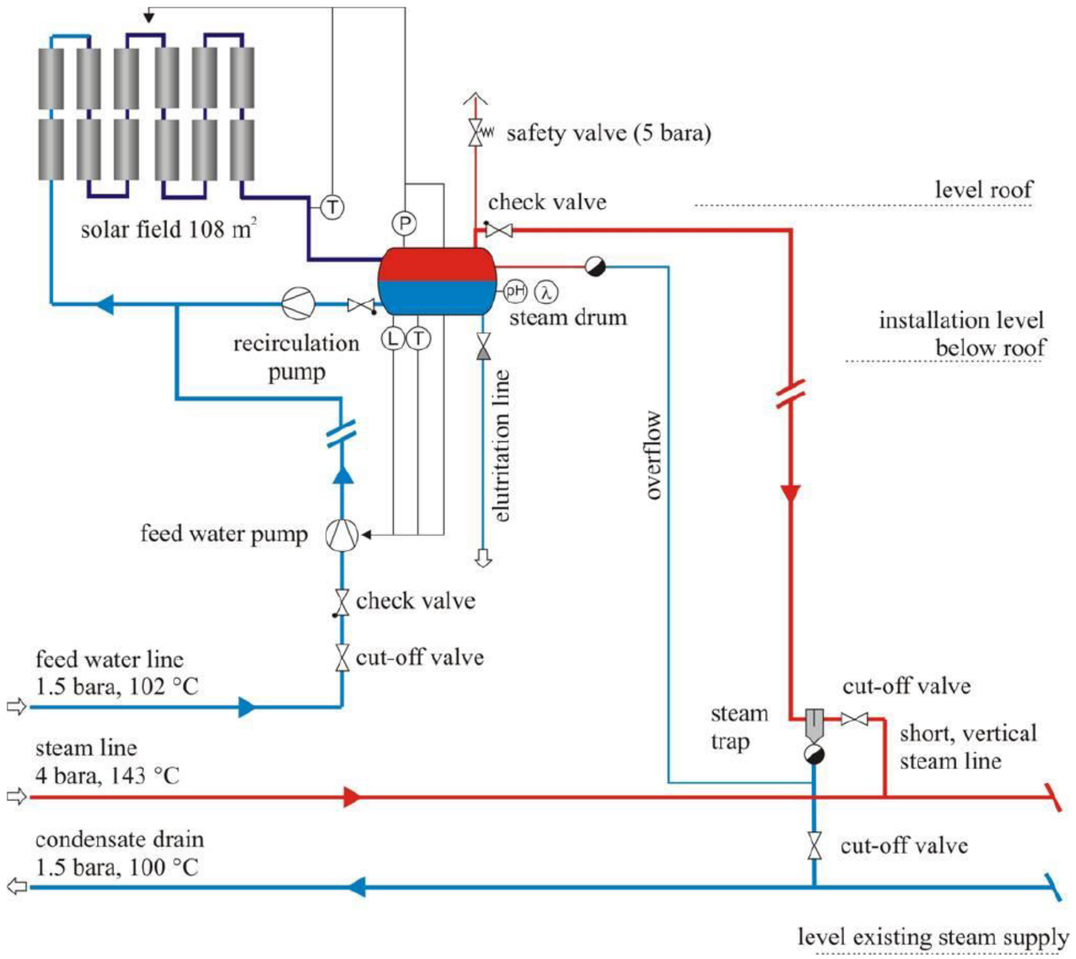


Figure 8.38: Layout of a direct solar steam integration system to be integrated at the ALANOD factory, Ennepetal, Germany (Hennecke, Hirsch et al. 2008).

8.3.4 Agriculture, forestry and fishing

There is complex relationship between primary production, energy inputs, water and land use including soil carbon, biodiversity, landscape and recreation. Large regional differences occur due to climate, seasons, weather patterns, terrain, soil types, precipitation, cultural practices, land use history and ownership, and farm management methods (extensive subsistence and low input (organic) farming or intensive, high input, industrialised farming).

Subsistence farming and fishing rely largely on human energy and animal power with traditional biomass from crop residues and fuelwood used for drying and heating applications (section 8.3.1.2). In contrast industrialised agriculture, forest and fishing industries depend on significant fossil fuel energy inputs that are either combusted:

- directly for heating, drying and to power boats, tractors and machinery, or
- indirectly to manufacture fertilisers and agri-chemicals; produce and transport imported feed; construct buildings and fences; and generate electricity for water pumping, lighting, cooling and operating fixed equipment.

Intensive agriculture as undertaken in USA typically uses on-farm twice as much energy directly as indirectly (Schnepf 2004), though this varies with the enterprise type. For some food products such as potatoes, the total energy inputs can exceed the food energy value of the harvested crop (as shown by a negative energy ratio of energy output/energy input) (Haj Seyed Hadi 2006). However this varies depending on the local farm management, the boundaries used and assumptions made, hence a positive energy ratio for potatoes has also been reported in Iran (Mohammadi, Tabatabaeefar et al. 2008).

In OECD countries, energy demand for the agriculture sector is typically around 5% of total consumer energy. Energy efficiency measures are being implemented and future opportunities exist to reduce fertiliser and agri-chemical inputs by using precision farming application methods (USDA 2009), improved manufacturing techniques and organic farming systems.

Primary producers can have a dual role as an energy user and as a supplier of energy carriers produced as co-products (Table 8.9)[18]. Landowners also have access to local RE resources including wind, solar radiation, potential and kinetic energy in rivers and streams and geothermal heat depending on land use, terrain and location.

Currently land use and land use change (agriculture and forests) accounts for around 30% of total greenhouse gas emissions (Metz, Davidson et al. 2007). CO_2 arises from fossil fuel energy inputs but most GHGs stem from deforestation, methane from ruminant digestion and paddy fields, and nitrous oxides from wastes and nitrogenous fertiliser use. Competition for land use to provide food, fibre, animal feed, recreation, biodiversity conservation forests, as well as energy crops is growing. Water use constraints, sustainable production and energy developments including biofuel production are under close scrutiny (Park 2008).

Rich multi-national corporate organisations and food importing countries such as Saudi Arabia, South Korea, Kuwait and Qatar have negotiated investments with governments of poor countries for between 15 to 20 M ha of land from 2006 to 2009. Their aim is to grow, manage and export food such as wheat, rice and maize, but also to produce crops for biofuel exports (Von Braun and Meizen-Dick 2009). Deals being quoted include China securing the right to grow palm oil for biofuel on 2.8M ha in the Democratic Republic of the Congo and also negotiating 2M ha in Zambia, South Korea investing in Madagascar, and Sun Biofuels UK, a private company, growing jatropha plantations for biodiesel oil in Ethiopia and Mozambique. Investments can either cause exploitation of the existing rural communities (WWICS 2010) or provide benefits when the advantages are equally shared, such as Brazilian sugar ethanol companies investing in Ghana (REW 2008).

A code of good conduct to share benefits, abide by national trade policies and respect customary rights of the family farm unit is being considered.

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[18] Note this section covers only on-farm and in-forest production and processing activities including harvest and post-harvest operations up to the farm gate. Food, fibre processing operations are covered in the Industry section 8.3.3.

Table 8.9: Primary production from industrial scale enterprises showing energy demand, energy use intensity (GJ/ha of land or buildings), RE carriers produced mainly for use on-farm and their potential for export across the farm boundary.

Type of enterprise	**Direct energy inputs**	**Energy use intensity**	**Potential renewable energy carriers**	**Energy export potential**
Dairying	Electricity for milking facility, pumping of water and manure, refrigeration. Diesel for tractor. Diesel or electricity for irrigation.	High. Medium. High if for irrigation.	Manure for biogas. Heat from milk cooling. Solar water heating. Solar PV.	Limited as most used on-site.
Pastoral grazing animals (e.g. sheep, beef, deer, goat, llama)	Electricity for shearing. Diesel.	Very low but higher if irrigated. Low or medium if some pasture conserved.	Hill sites for wind turbines. Hydro power options. Solar systems on buildings. Green crops for biogas.	Wind power. Biogas CHP (combined heat and power).
Beef-lot, intensive production	Electricity for lighting, cooling, water pumping. Diesel for tractor.	Medium. High for harvesting feed.	Manure for biogas CHP. Solar PV and/or solar thermal if roof space available.	Limited as used on-site.
Pigs	Electricity for lighting, heating, cleaning.	High if housed indoors. Medium if kept outdoors.	Manure for biogas. Solar if roof space available.	Limited as used on-site.
Poultry	Electricity for lighting, heating, cleaning.	High if housed indoors. Low if free-ranging.	Combustion of litter for CHP. Solar systems.	High. Several multi-MW power plants operating in UK, US.
Arable (e.g. wheat, maize, rapeseed, palm oil, cotton, sugarcane, rice etc.).	Diesel. Electricity for storage facilities, conveyor motors, irrigation. Gas or LPG for drying.	Very high for machinery. Medium if rainfed. High if irrigated. Low and seasonal.	Crop residues for heat, power and possibly biofuels. Energy crops. Hydro power if streams suitable.	High where energy crops are purpose-grown.
Vegetables large scale (potatoes, onions, carrots, etc.)	Diesel. Electricity for grading, conveying irrigation, cooling.	High for machinery. High if irrigated and for post-harvest chillers.	Dry residues for combustion. Wet residues for biogas.	Limited if used on site.
Market garden - vegetables small scale (mixture)	Diesel for machinery. Electricity for washing, grading.	Medium. Low for post-harvest. Medium if cool-stores.	Some residues and rejects for biogas but usually too small a resource for on-site use.	Low.

Nursery cropping	Diesel for machinery. Heat for protected houses.	Low. Medium.	Some residues and rejects for combustion.	Low.
Greenhouse production	Electricity for ventilation, lighting. Gas, oil, or biomass for heat.	High where heated. Medium if unheated.	Small volumes of residues and rejects for combustion.	Low.
Orchard (pip fruit, olives, bananas, pineapple etc.)	Diesel for machinery. Electricity for grading, drip irrigation, cool-store etc.	Medium. Medium if irrigated and post-harvest storage.	Prunings for heat. Reject fruit for biogas.	Low.
Forest plantations (eucalyptus, spruce, pine, palm oil, etc)	Diesel for planting, pruning and harvesting.	Low.	Forest residues. Short rotation forest crops. Spent oil palm bunches.	High – large volumes of biomass for CHP or possibly for biofuels.
Fishing – large trawlers off-shore	Marine diesel/fuel oil. Electricity for refrigeration.	High.	(Reject fish dumped at sea).	None.
Fish farm – near-shore or on-shore.	Diesel for boats for servicing. Electricity for refrigeration.	Low or medium if facilities off-shore. Medium.	Fish wastes for biogas and oil. Ocean energy.	Low. Electricity from ocean energy possible in future.
Fishing – small boats near-shore.	Diesel/gasoline. Electricity for ice or refrigeration.	Low. Low.	Fish wastes for biogas and oil.	Low.

8.3.4.1 Status and strategies

The integration of land use with the development of RE projects for electricity generation is well established. For example, wind farms constructed on pasture and crop lands provide multi-purpose land use and additional revenue to the landowner since only 2 to 3% of the total land area is taken out of agricultural production for access roads, turbine foundations and control centre buildings. Similar opportunities exist for small and large hydropower projects (although social disbenefits for local residents can also exist – see Chapter 9). Many sites in Europe and elsewhere that used to house water mills could be utilised for run-of-river micro-hydro power generation schemes and low head turbines have been developed for operating in low gradient water distribution channels to power irrigation pumps (EECA 2008).

Solar thermal systems have been commonly used for water heating but solar sorption technologies for air-conditioning, refrigeration, ice making, and post-harvest chilling of fresh products remain at the development stage (Fan, Luo et al. 2007). Geothermal heat has been used for various thermal applications including for heating greenhouses, heating water for fish and prawn farming (Lund 2002), desiccation of fruit and vegetables, heating animal livestock houses and drying timber.

Biomass resources produced in forests and on farms are commonly used to meet local agricultural and rural community energy demands. Although many examples exist, developing a bioenergy project can be challenging in terms of securing biomass feedstock for the long term, ensuring it is sustainably produced, storing it for all-year-round use with minimal losses, transporting it cost-effectively due to its relatively low energy density compared with fossil fuels, recycling nutrients and obtaining planning consents (IEA 2007).

Anaerobic digestion of animal manures, food and fibre processing wastes, or green crops to produce biogas is a well understood technology (Chapter 2). Gas storage is costly, so matching supply with demand is a challenge for the system designer. The odourless, digested solid residues can be used for soil conditioning and nutrient replenishment. Fish processing residues can also be utilised, though they tend to be dried and ground for animal feed or fertilisers. On-farm use of biogas for heat, or CHP using gas engines, is common practice. A less common application is as a transport fuel similar to compressed natural gas (CNG).

Dry crop residues produced during processing are in effect delivered free-on-site. Rice husks, coconut shells etc. are easily stored and commonly combusted at the small scale for heat generation or at a larger scale for CHP. Bagasse (fibrous residues from sugarcane), at around 50% moisture content (wet basis), has traditionally been combusted inefficiently to provide sufficient heat and power to supply the refinery but mainly to avoid a costly disposal problem. Privatisation of the electricity industry in many countries has enabled sugar plant owners to invest in more efficient CHP plants that generate excess power for export. Partly drying the bagasse with available heat to give more efficient combustion, and with reduced air pollutant emissions, could be warranted (Shanmukharadhya and Sudhakar 2007).

Cereal straw or forest residues have to be collected and transported as a separate operation following the harvest of the primary product (grain or timber). Due to the additional costs involved, techniques for integrated harvesting of these co-products have been developed such as whole crop harvesting with later separation, or whole tree extraction to a landing where the tree is processed into various products (Heikkilä, Laitila et al. 2006).

8.3.4.2 Pathways for renewable energy adoption

Much cultivated land could simultaneously be used for RE supply, in many cases best utilising the energy on the property to displace imported energy needed to run the enterprise (Table 8.9). Fish enterprises may be able to utilise local waves or ocean currents for power generation opportunities in the future (Chapter 6). Market drivers for RE power generation on rural land, coastlines and waterways include electrification of rural areas, energy security and the avoidance of transmission line capacity upgrading where loads are increasing.

Little surplus land is available for bringing into cultivation in most countries and further deforestation is not an acceptable option. Therefore to meet the growing demands for primary products including biomass, increasing productivity of existing arable, pastoral and plantation forest lands by improving management and selecting higher yielding varieties is one option. (Changing diets to eat less animal products is another). Through these actions, average yields of staple crops have continued to increase over the past few decades (Fig. 8.39) though with variations between regions. This trend could continue over the next few decades, with genetically modified crops possibly having a positive influence. Conversely, global warming trends have possibly already offset some of the productivity gains expected from technological advances (Lobell and Field 2007).

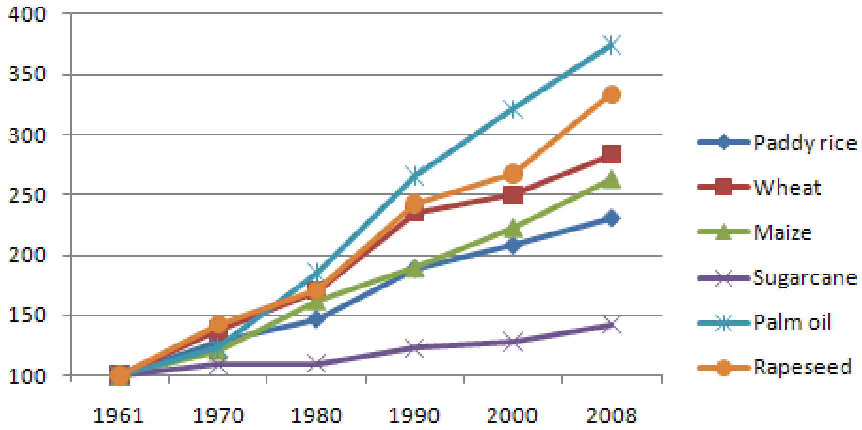


Figure 8.39: Increased productivity per hectare for a range of crops over the past few decades compared with base year 1961 (FAO 2009).

8.3.4.3 Transition issues

The primary production sector is making a slow transition to reducing its dependence on energy inputs as well as to better using its naturally endowed, RE sources. Multi-uses of land for agriculture and energy purposes is increasing but the share of the total potential being utilised at present is miniscule. Barriers to greater deployment include high capital costs, lack of available financing, remoteness from energy demand (including access to electricity and gas grids), competition for land use, transport constraints, water supply limitations, and lack of skills and knowledge by landowners.

8.3.4.4 Future trends

Distributed energy systems based on RE technologies are beginning to gain support in cities (IEA 2009) but also have large potential in rural areas. The concept could also be applied to produce mini-power distribution grids in rural communities in developing countries where electricity services are not yet available.

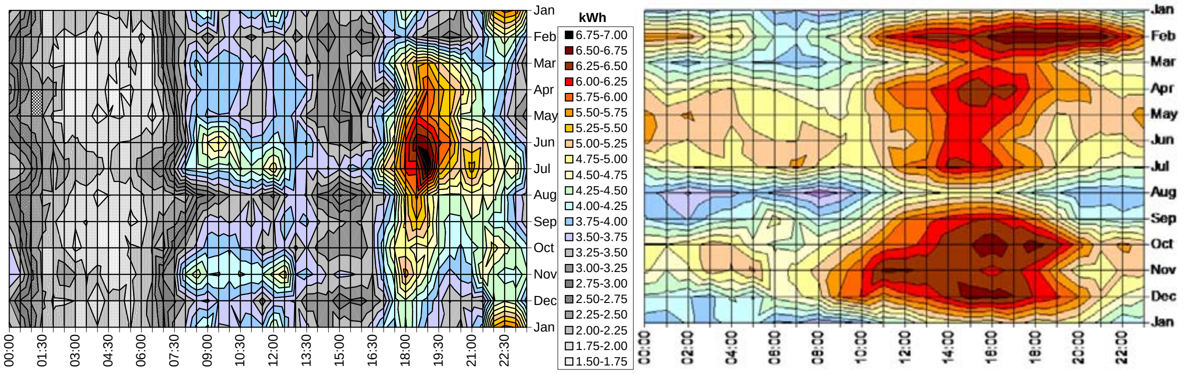
A future opportunity for the agricultural sector is the concept of carbon sequestration in the soil as “bio-char” (Lehmann 2007). When produced via gasification or pyrolysis using the controlled oxygen combustion of sustainably produced biomass, incorporation of the residual char into arable soils is claimed to enhance future plant growth and the carbon is removed from the atmosphere (Verheijen, Diafas et al. 2010). Further RD&D is required to assess soil suitability, impacts on crops yields, methods of pulverisation and integration but the future integration potential, once proven, could be significant

8.3.4.5 Case study

Distributed generation in a rural community. Distributed energy systems for rural communities can provide climate change mitigation benefits, lead to sustainable development, give increased security of supply and provide revenue to landowners. A small demonstration project at Totara Valley, New Zealand aims to:

- demonstrate a methodology for local energy resources to be easily identified and utilised to meet local demands for heat and power in order to provide economic and social benefits;
- identify new business opportunities for power distribution companies and circumvent the commercial challenge of having to supply their more remote customers; and
- solve the technical problems of supplying heat and power to multi-users from several small generation sites within a given locality using RE resources wherever feasible.

Electricity meters at strategic locations measured demands of the appliances used in the woolsheds, houses, workshops, freezer sheds etc. (Murray 2005) and enabled a series of electricity profiles to be produced showing both seasonal and daily variations (Figure 8.40). The wind speed and solar radiation resources were monitored and a method developed to show seasonal and daily variations.



(a) (b)

Figure 8.40: Average seasonal and daily electricity demand for the Totara Valley community households in kWh consumption per 30 minute periods (a) with annual and daily wind data (b) showing a reasonable match with the demand (Murray 2005).

A 2.2kW wind turbine was installed on the best hill site, but due to the cost of 1.5km of copper cabling being around 2005 US$ 13,000 it is used to power an electrolyser (Sudol 2009) with the hydrogen produced piped down to a fuel cell with storage and transfer losses of only around 1%. A 1kW Pelton micro-hydro turbine was installed. Since wind and solar are variable and not all properties have a reliable stream with micro-hydro potential, matching power supply with continually varying demand is difficult and often requires some form of storage if not being grid-connected as in this example. Suitable controls and smart metering systems will help integrate various generation technologies between users and the local grid, and enable metering of both imported and exported power to be achieved (Gardiner, Pilbrow et al. 2008).

A power distribution company could have a strong business interest in becoming a joint venture partner in such a scheme, to buy and sell electricity but also to sell or lease the power generation equipment to the community members. A related study from the line company perspective (Jayamaha 2003), modelled different scales of communities in detail (Figure 8.41) to show benefits arise from having larger communities.

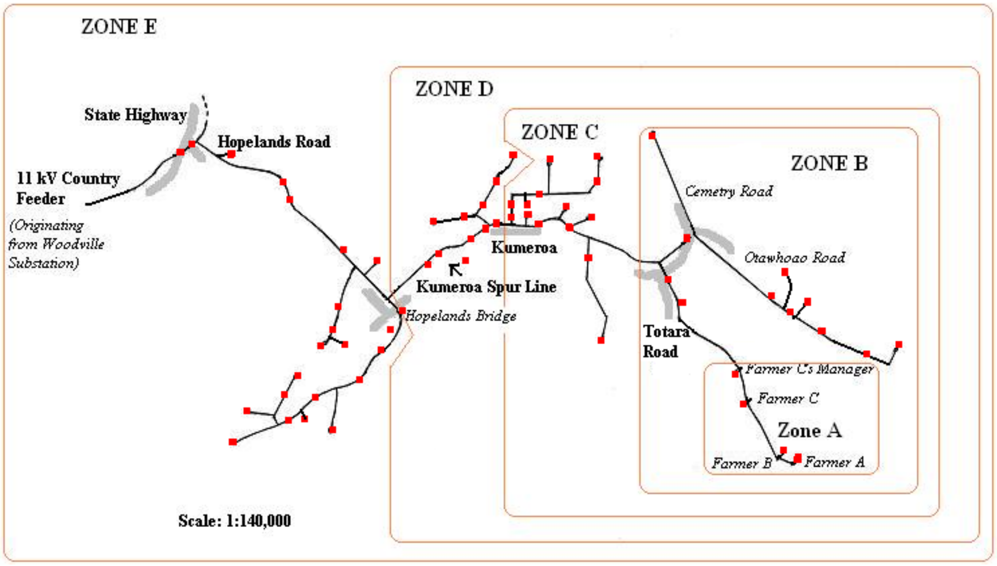


Figure 8.41: The power distribution feeder reaching Totara Valley (Zone A) is the end of the line. House and other building clusters with power loads are shown as red squares. The larger the scale of community using their local RE resources (Zones A, B, C, D or E), the greater economic benefits of the system (Jayamaha 2003).

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