A More Perfect Union

Energy Systems Integration Studies from Europe

By John Holmes

THE MAIN AIMS OF THE ENERGY POLICY OF THE EUROPEAN Union (EU) are 1) to establish a European energy system that is sustainable (particularly with respect to reducing greenhouse-gas emissions) and enhances Europe's competitiveness and 2) to improve the security of energy supplies to Europe's 500 million inhabitants. A key element of Europe's strategies to achieve these aims is to establish a more integrated energy system in which there is a well-connected and competitive market, particularly for gas and electricity. A pan-European energy infrastructure (analogous to those in place in other sectors of long-term public interest, such as telecommunications and transport) is seen as an essential enabler.

The European Academies Science Advisory Council (EASAC) was established in 2001 by the national science academies of the EU member states to provide independent advice to EU policy makers on the science underpinning key policy decisions. Reflecting the EU's policy priorities, issues of energy systems integration have been an important concern of EASAC's program of energy studies.

This article summarizes the energy systems integration issues addressed in four studies undertaken by EASAC over the last four years and draws some cross-cutting conclusions on the challenges associated with the analysis, design, and operation of integrated energy systems and how they may be met. The four studies summarized in the following sections are:

- ✔ a review of how the European electricity grid needs to be developed to support EU policy goals to create a pan-European electricity market and to increase substantially the generation of electricity from renewable sources

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- ✔ an evaluation of the current status and development challenges of concentrating solar power; its consequent potential contribution in Europe, the Middle East, and North Africa; and the actions necessary to enable that contribution to be realized
- ✔ a review of the impacts of biofuels and their environmental sustainability
- ✔ an examination of the challenges that must be addressed at an EU energy system level to secure carbon capture and storage (CCS) as a viable component of strategies to mitigate climate change, and an evaluation of the contribution that CCS may therefore make to achieving Europe's energy policy goals up to 2050.

Before presenting the four studies, some further background is provided on the EU energy policy context.

Energy Policy in the EU

The EU has established ambitious energy and climate change objectives. EU targets for 2020 include a 20% reduction in greenhouse-gas emissions (rising to 30% if international conditions permit) and an increase in the share of renewable energy to 20%. In the longer term, a commitment has been made to substantially decarbonize energy supply, with a target of reducing EU greenhouse-gas emissions by 80–95% (compared with 1990 levels) by 2050. Reaffirmed by the European Council in February 2011, this objective requires the EU's electricity system to achieve essentially zero emissions of greenhouse gases by 2050. The central goals of EU energy policy—security of supply, competitiveness, and sustainability—have been laid down in the Lisbon Treaty.

Renewable energy sources are anticipated to play a major role in achieving these longer-term targets. A plan known as the European Strategic Energy Technology Plan (SET-Plan) was developed in 2007 to accelerate the development of low-carbon technologies and was subsequently endorsed by the EU in light of the conclusion by the Second Strategic European Energy Review that "the EU will continue to rely on conventional energy technologies unless there is a radical change in our attitude and investment priorities for the energy system." An updating of the SET-Plan in 2013 emphasized the need for energy systems integration.

A key concern of the EU's energy policies and initiatives is that electricity and gas supplies are still largely fragmented into national markets with inadequate physical interconnections and with numerous barriers to open and fair competition. The European Commission's communication on energy infrastructure priorities for 2020 and beyond, issued in November 2010, therefore called for a new EU infrastructure policy to optimize network development for electricity, gas, oil, and CO_2 on a continental scale. Subsequently, regulations have been proposed aiming at the full integration of the internal energy market and to streamline permitting procedures for key transnational infrastructure projects, together with market-based and direct EU financial support mechanisms.

Europe's energy strategy also identifies the development of strong international partnerships, particularly with neighboring countries, as a key priority. It includes actions to integrate energy markets and regulatory frameworks with neighboring countries and the launching of a major cooperation with Africa on energy initiatives. Development of new electricity and gas interconnections with neighboring regions has been identified as an associated necessity. The "energy system" that must be addressed therefore increasingly extends beyond the borders of Europe.

The European Electricity Grid

As indicated above, European energy policy seeks to create a pan-European, competitive electricity market and to substantially increase the generation of electricity from renewable resources. In the coming years these two factors will require significantly increased transfer of large amounts of electrical energy across long distances and national borders in Europe. Historically, each country designed and built its electricity supply grid primarily to meet its own needs, and there have generally been rather limited transfers of electrical energy between countries. If energy policy goals are to be achieved, a more integrated European grid needs to be developed: one that can enable a competitive electrical energy market and support the optimization of Europe's use of electricity from renewable sources while maintaining the current high levels of reliability of electricity supply.

The first of the four EASAC studies therefore identified how the European electricity transmission grid needs to be developed if it is to enable the achievement of these policy goals. The energy system integration issues addressed by the study were the planning and development of the European grid and the physical and market aspects of its operation.

For the planning and development of a European grid to ensure that investments in capacity to transmit electrical energy are made in the right places, the study concluded that a much better coordinated and harmonized approach to planning is needed, based on common grid-planning principles, practices, and scenarios. The common grid-planning principles should be mandatory for transmission system operators (TSOs) and defined at the European level for short- and long-term planning. They should define the way future requirements are created as well as the credible faults and their acceptable consequences. Further, the plans created in consequence must be regularly updated.

Given the scale of the European grid, a combination of top-down and bottom-up planning processes, all operating in a well-understood framework, will be required. Uncoordinated local decisions will inevitably lead to difficulties. Decisions need to be taken about the operational security of supply for Europe as a whole, but further research and development with respect to appropriate planning approaches are needed. Increased use should be made of revenues generated through congestion management to fund investment projects to strengthen transmission capacity.

To support a more coordinated and harmonized planning approach, common European models of the grid and the electricity market need to be developed (through collaboration on the part of the TSOs). These should be able to simulate power flows, power and energy exchanges, and the economics of electricity generation and transmission. The models should be underpinned by better sharing of grid data.

The successful realization of an effective European transmission system will require that human resources with the necessary skills be put in place. This capacity must be planned for, and appropriate schemes for training and career development must be established.

The operation of the European grid to ensure that the maximum benefit is extracted from a given infrastructure will need to be done using a more coordinated approach that is based on substantially enhanced levels of data sharing. This coordination is needed in the first instance at the policy level, then during the proper physical development of the infrastructure, and finally in the operational period. The *operational period* covers issues from maintenance planning and day-to-day physical scheduling of power flows all the way down to real-time, secure operation. In parallel with the physical system, there is a need for transparent market mechanisms that will produce the correct price signals to ensure efficient grid development and operation. The market must be compatible with the physical infrastructure and operations. This complex coordination involves policymakers, regulators, TSOs, grid owners, market operators, and market participants. There need to be clearly defined responsibilities, especially in emergencies.

To the extent that incentives and subsidies are used, this first EASAC study concluded that they need to be harmonized across Europe to obtain an optimal transmission system and give the correct price signals. Congestion should be managed in a coordinated manner across the entire European Union system. As the system becomes more integrated, there will be an increasing need for European Union–wide control systems based on real-time information from advanced telemetry and the use of activating controls in real time. This may require further research and development.

Issues of demand-side participation will need to be addressed, and a better understanding should be developed of the implications for electricity transmission of developments in load diversity, e.g., as a result of the large-scale introduction of heat pumps or electric cars.

Concentrating Solar Power

Concentrating solar power (CSP) sits alongside photovoltaic electricity generation as a commercially available renewable energy technology capable of harnessing the immense solar resource in southern Europe, the Middle East and North Africa (the MENA region), and elsewhere. With CSP, a high-temperature heat source is created by concentrating the sun's rays to produce electricity in a thermodynamic cycle (see Figure 1). The energy systems integration issues addressed in EASAC's study of CSP included evaluating the value of CSP generation and considering the challenges and benefits of geographic integration and the associated issues of economic and political integration.

Taking into account the internalizing of the costs of CO_2 emissions for coal- and gas-fired power plants (through addition of CCS or payments for CO_2 allowances in the EU's emissions trading scheme), the anticipated reduction in CSP generating costs of around 60% over the next 10–15 years should enable CSP to be cost-competitive with fossil-fired power generation by the mid-2020s. Over the interim period, the study concluded that markets should be better integrated to extend market opportunities and facilitate progress along the cost curve and that incentive schemes to subsidize renewable energy generation should be extended and harmonized across Europe and designed to:

- ✔ reflect the true value of electricity to the grid (otherwise, CSP plants may be inappropriately designed)
- ✔ effectively drive research and development by ensuring that market realities are strong drivers and enabling the market entry of technology breakthroughs
- ✔ ensure transparency of cost data so that an accurate picture of learning rates is available
- ✔ progressively reduced subsidies over time.

CSP should be viewed as an integrated "project" undertaken over the 40-year period to 2050, in which CSP development in Europe and the MENA region has an initial investment phase lasting 10–20 years and involving

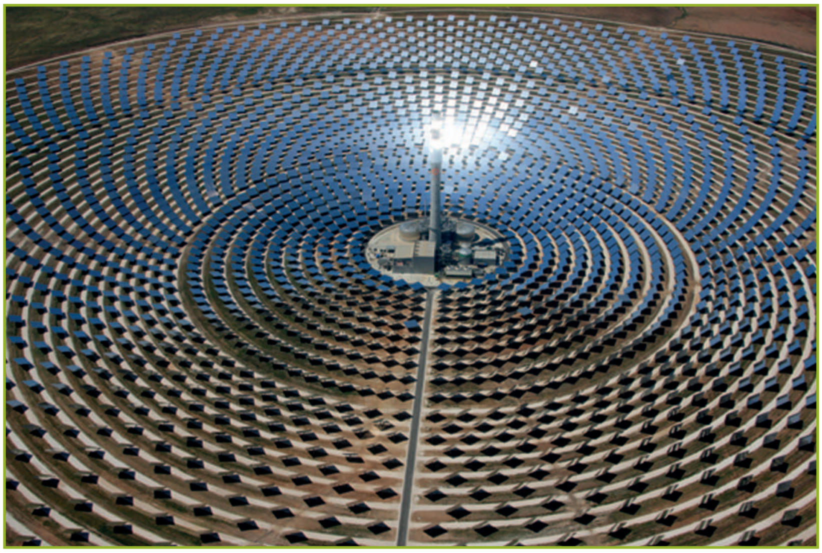

figure 1. Heliostat at Torresol Energy's Gemasolar plant in Andalucia, Spain. (Photo courtesy of Torresol Energy.)

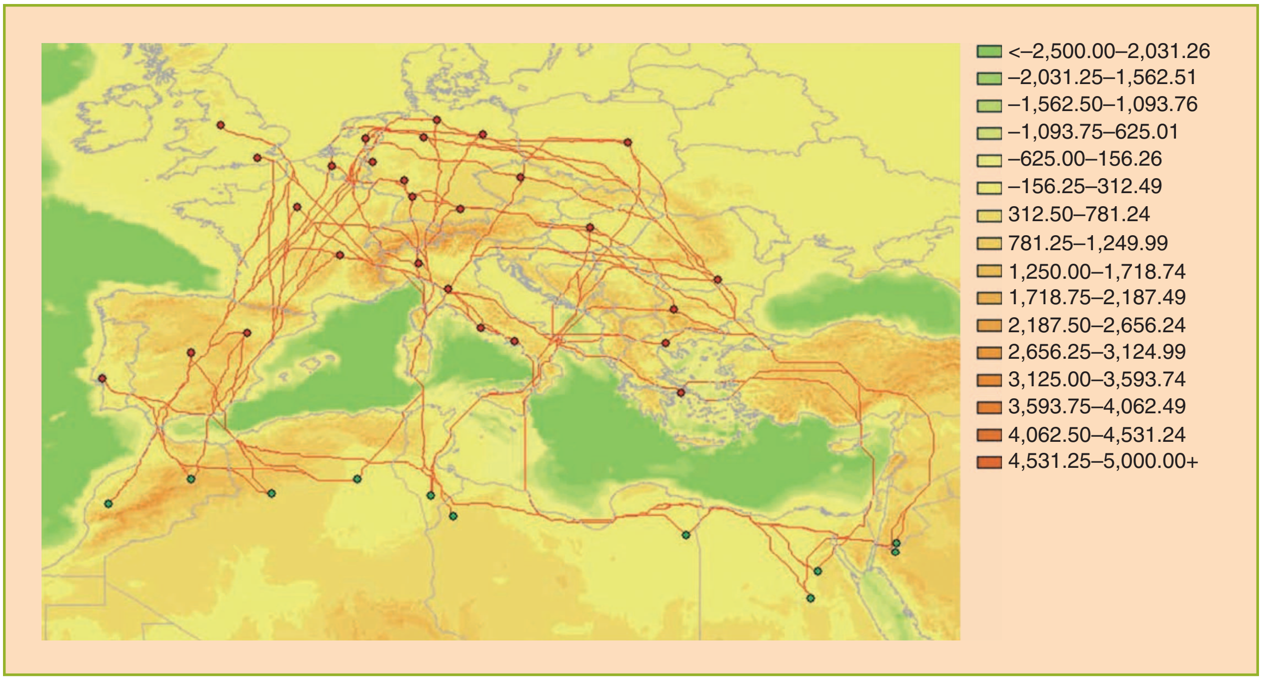

figure 2. Exploration of potential transmission routes for HVdc lines connecting CSP plants in the MENA region to demand centers in Europe. The background map shows elevation in meters above or below sea level. (Image courtesy of DLR.)

incentive payments measured in billions or tens of billions of Euros (depending on whether the learning rate in practice is at the high or low end of the range of possibilities), resulting in a payback over the subsequent period to 2050 and beyond, with returns that depend on the value ascribed to avoiding CO_2 emissions and on future fossil fuel prices.

A distinctive characteristic of CSP in relation to many other renewable energy sources is the potential it offers for incorporating storage at relatively low cost, enabling a CSP power plant to provide dispatchable power. Overly simplistic claims have been made about the value of such storage, however. Informed by associated simulation studies of the Iberian electricity system, the EASAC study concluded that the economic value of thermal energy storage for a CSP plant cannot be calculated at the plant level but only at the system level: the overall configuration of the electricity system determines the price curve and hence the value of shifting the timing of generation through the day. Generally speaking, the higher the share of solar power within the system, the less pronounced the diurnal price curve will be, reflecting a need to use solar power at times other than the midday peak as solar generating capacity increases. This implies that thermal energy storage is less relevant today (at low solar shares), but may rise over time (with increasing solar shares).

It was concluded that further simulation studies of the European electricity system should be undertaken, including the use of high-resolution and (ideally) stochastic power system models, to look at interaction effects for different shares of renewable energy sources at the EU, MENA, and EU-MENA levels of power system integration. The knowledge gained from these studies, together with data on the learning rates of CSP and PV technologies, should be used to guide the development of the optimal mix with which to harness solar resources.

The solar resource in southern Europe is such that CSP could provide a useful contribution to achieving Europe's aim of a zero-carbon electricity system by 2050. Solar resources in the MENA region are even better and far larger. Once CSP achieves cost parity with fossil-fired generation, these resources have the potential to transform the system of electricity generation in Europe and the MENA region (see Figure 2). But they bring major challenges in achieving the required physical, market, and political integration.

The development of CSP in the MENA region is a potentially significant component of initiatives to support low-carbon economic development and political progress in the region, as reflected in the Barcelona Process, the Deauville Partnership, and so on. CSP technologies (unlike some other renewable energy technologies) lend themselves to high levels of local deliverables, well matched to the capabilities of the workforce and the needs of industries in the region.

Given the rapidly increasing demand for electricity in MENA countries, much of the electricity generated by CSP plants in the MENA region over the short-to-medium timescale may—and should—be expected to be used locally rather than exported to Europe, thus avoiding the construction of fossil-fired capacity in the MENA region. Financing schemes and associated political agreements between the EU and MENA countries will be needed to enable these developments

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in the short-to-medium timescale. But without financial commitments on the order of billions of Euros from Europe, renewable energy technologies, including CSP, are unlikely to develop quickly in the MENA region.

The challenge is to take a coordinated approach, simultaneously addressing the various bottlenecks (investment protection, energy policy incentives, R&D, and so on), and to identify options that lower the barriers to entry for other actors. For this purpose, the study recommended that a transformation process should be defined that addresses the technical, political, and socioeconomic factors necessary to achieve integration of EU and MENA energy systems and to strengthen the implementation of renewable options in the MENA region. The EU should develop cofunding and cofinancing options for CSP in the MENA region at a substantial scale as part of its neighborhood policy.

Sustainable Biofuels

As a component of its strategy to achieve a 20% renewable energy contribution in 2020, the Renewable Energy Directive in 2009 established a requirement on EU member states that 10% of the final consumption of energy in transport should come from renewable sources. Given systems limitations and technology availability, this primarily means the use of first-generation biofuels made from the edible parts of plants. The EASAC biofuels study responded to widespread concerns about the use of biomass for producing road transport fuels and about the arrangements for ensuring that such fuels provide a real climate benefit while not harming the wider environment. The main system integration issues addressed by the study are summarized here—notably, the scope of systems analysis; the integration of food and fuel systems; and the establishment of optimal systems and routes to harnessing the sun for transport.

The two main considerations that arise in respect of the scope of systems analysis are 1) establishing that biofuels meet specified levels of greenhouse-gas reductions compared with fuels made from crude oil and 2) protecting biodiversity from the negative impacts of biofuels production.

The study concluded that the methods of life cycle analysis prescribed by the Renewable Energy Directive are incomplete and do not take a sufficiently broad view of the pertinent system. They fail to account for some major sources of greenhouse-gas emissions, including aspects of carbon storage and the secondary impacts of biomass cultivation known as indirect land use change. When these sources are taken into account, it appears that the reductions in emissions achieved by first-generation biofuels generally do not meet the 2018 criterion (that greenhouse-gas savings from use of biomass should be at least 60%) and that in some cases they do not meet the current criterion (a 35% threshold) either. A revision of the methods of life cycle analysis to take full account of emissions arising in biomass cultivation is therefore required.

It was also concluded that the biodiversity criteria are inadequate in scope, with important areas for conservation of biodiversity left unprotected, and, crucially, that the criteria do not fully allow for the effects of indirect land use change. The criteria for biodiversity protection should therefore be revised. To prevent the worst effects of indirect land use change, measures to protect biodiversity should be enacted for all agricultural production, not just for biofuels. Unless the system is extended to all agricultural use of land and consistent criteria for protection of biodiversity are applied across the board, demand for land for biofuels would create a distortion: areas where it is relatively straightforward to provide proof that sustainability criteria are met could be taken for biofuels while food production is moved to areas where it might be more difficult to demonstrate conformity.

With regard to the integration of food and fuel systems that inevitably results from biofuels production, a measure of the scale of the issue in Europe is that the energy content of fuel corresponding to the 10% target (350 TWh) is roughly equivalent to the energy contained in the EU production of food. Global-level assessments of the potential for energy from biomass (not just biofuels) range from less than 10% of global energy supply to more than 100%. Assumptions about future food consumption are crucial to the demand side of these assessments, and the same is true of assumptions about future yields and the availability of land on the supply side. They also typically assume the availability of second-generation technologies (discussed below) and do not take full account of broad sustainability considerations, including the possible climate and environmental risks associated with intensive agriculture.

The current technology for biofuel production depends on feedstock derived from the edible fraction of food plants. There are therefore concerns about competition between food and fuel. Evidence for this has been found in the form of rising food prices associated with increases in biofuel production. An EU study, *Biofuels Baseline 2008,* concluded that the impact of EU biofuels consumption has been to increase food prices, with modest increases in the case of cereals but with a major impact on prices of food oil.

Considerations of food security in the context of the increasing demand for food and fodder to meet the needs of a growing global population suggest that there will be continuing pressures on edible plant material, which the study concluded should exclude its use in biofuel production. Instead, the preferred route for biofuels in the future should be through second-generation biofuels based on the *inedible* parts of plants, including straw, wood, and waste streams (which should be available for commercial-scale production from 2020 onwards), and third-generation biofuels based on algae (which will only become commercially available much later).

Even here, careful consideration is needed as to whether any associated increase in the cultivated land area of Europe would be better used to offset imports of food, thereby improving food security, or to produce biomass for biofuels. If such analysis shows that food production is the better option, then the increased biomass production required for the EU 2020 target would have to come mainly from imports, with the consequence that environmental risks would be exported.

The study noted that substantial amounts of food are lost after harvest and that this material constitutes a large, compostable resource for the production both of biogas and of solid by-products that could usefully be returned to the soil. This leads to a consideration of the optimal systems and routes to harnessing the sun for transport. Insufficient attention has so far been given to systematic analysis of the alternatives, including reducing the demand for transport and increasing its efficiency.

Solar energy, for example, is more efficiently captured by photovoltaics than algae, so that the cost-benefit balance of using algae to produce advanced biofuels is not obvious, given the alternative of photovoltaic generation of electricity to power road transport by batteries or electrified railways. Similarly, assuming that there are supplies of biomass from agriculture or forestry, it is not clear that even second-generation biofuel production is the most efficient means of using it for energy. This is partly because of the energy consumed by the production of biofuels and partly because the internal combustion engine is inefficient as a means of converting stored energy to useful work. Direct combustion, in combined heat and power (CHP) plants for example, offers potentially greater energy recovery when the electricity is used directly in the light-duty parts of the road transport fleet. This is relevant only where there is a substantial electric vehicle fleet, however, which is not anticipated in Europe before 2020.

This comes into sharp focus in the case of the heavy-duty fleet, where electricity is not an option for the foreseeable future. For heavy-duty transport and the diesel cycle, the only real options are biodiesel and biogas. Although many European countries have extensive distribution networks for gas, biogas for road transport suffers from the disadvantage of a lack of refueling infrastructure and so is likely to remain a niche fuel for centrally fuelled fleets. This leaves biodiesel as the most effective short- to midterm (post-2020) alternative. If a suitable refueling infrastructure can be established, however, biogas would be a strong contender in the market for fuel for heavy-duty vehicles.

There are also potential benefits to the EU electricity system in the use of biofuels. The electricity system requires supply and demand to be continuously in balance, and as the anticipated future EU electricity system will rely heavily on variable renewables such as solar power and wind, biofuels can be helpful in achieving this.

In summary, any future revision of EU policy should take an integrated approach across policies for energy, transport, and agriculture, and a sufficiently broad and long-term view of the system to be optimized.

Carbon Capture

CCS is the process whereby carbon dioxide resulting from the use of fossil fuels in power stations and industrial processes is captured before it is released to the atmosphere and then transported to a secure underground storage facility (see Figure 3). CCS is an important component of the EU's policies and strategies for mitigating climate change. But experience with commercial-scale operation is limited, and progress on developing CCS in Europe has stalled in recent years.

The EASAC CCS study therefore examined the challenges that must be addressed to secure CCS as a viable component of EU strategies to mitigate climate change and, consequently, to consider what contribution it may make in Europe up to 2050. The energy systems integration issues it addressed included European-level integration of CO_2 transport and storage infrastructures; "cradle to grave" management of fossil carbon; incentive structures for CCS; assessment of environmental impacts; and the integration of different industries in developing CCS schemes.

A strategic approach to developing an integrated CO_2 transport infrastructure for Europe as a whole will lead to a substantially cheaper outcome requiring fewer transport corridors (and hence fewer planning permissions that are potentially difficult to acquire) than if a piecemeal approach is taken. Savings have been estimated as 25–40% compared to uncoordinated point-to-point connections.

A necessary precursor is a much better fix on the locations of Europe's storage capacity; the necessary investment in establishing the location and characteristics of Europe's CO_2 storage capacity should therefore appropriately be made at the EU level. A regional approach should be taken, enabling the strategic integration of sources, storage sites, and CO_2 transport networks and founded on an iterative identification and characterization of storage capacity.

A significant challenge will be to put in place financing mechanisms that will enable this transport infrastructure to be developed and particularly to address the issue

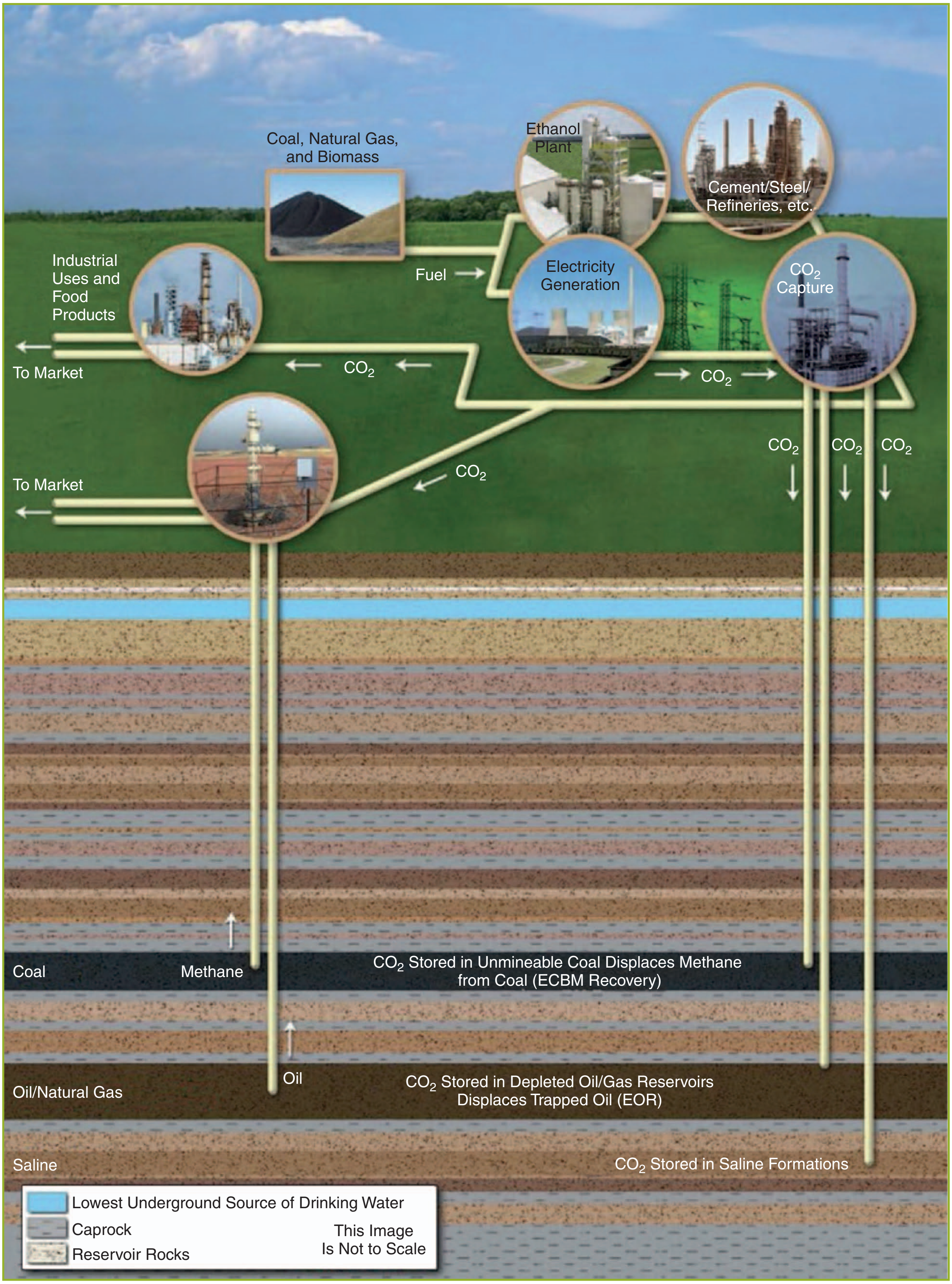

figure 3. Illustration of CCS. (Image courtesy of the U.S. Department of Energy.)

> There are many opportunities to improve the overall performance of energy systems with increased levels of integration, but this improvement comes with significant challenges.

that pipelines will initially need to be oversized to allow for the progressive connection of sources and storage facilities. Additional challenges that need to be addressed to secure an integrated CO_2 transport and storage system include:

- ✔ reducing permitting times for infrastructure projects through streamlining permit granting procedures and by means of effective public engagement mechanisms that will secure the necessary levels of public support
- ✔ developing common entry specifications for the pressure and temperature of CO_2 streams feeding into trunk mains, together with requirements on the impurities they contain which may otherwise compromise the integrity and safe operation of the CO_2 pipelines.

Inherently, the adoption of CCS reflects a more integrated "cradle to grave" approach to managing fossil carbon in energy systems based on coal, oil, and gas. This is particularly apparent in the combination of CCS with enhanced oil or gas recovery. It is anticipated that such initiatives may provide early opportunities for deployment of CCS in Europe by providing an income stream to offset the costs of CCS, as has already been the case in North America.

The EASAC study concluded that the core of CCS's contribution to meeting the EU's greenhouse-gas reduction targets would lie in CCS applications with favorable juxtapositions of sources, sinks, and public acceptance, and from an electricity systems point of view, in enabling fossil-fired power stations to play a key role in balancing supply and demand in an electricity system with close to zero greenhouse-gas emissions relying primarily on renewable energy sources. Positioning CCS in this way may help to overcome opposition founded on a belief that the pursuit of CCS will come at the expense of developing renewable sources. It requires demonstration, however, that power stations with carbon capture, together with their associated CO_2 transport and storage facilities, can operate reliably in a variable-load regime.

The cost of CO_2 emissions, as reflected in EU allowances prices in the European Emissions Trading Scheme, had been anticipated to provide sufficient incentive for the deployment of CCS. But EU allowances prices have collapsed due to oversupply, and additional incentives are now being considered to enable demonstration and first-generation commercial plants to proceed.

While the price of CO_2 emissions must be sufficiently high to incentivize deployment of CCS in Europe, care must be taken in pushing forward CCS that carbon-intensive industries are not driven to other regions where there are fewer restrictions (carbon leakage). Well-designed packages of regulatory and financial measures will be needed to avoid this problem and will need to be kept under review in light of progress elsewhere in the world. The EU should continue to influence developments globally to secure the introduction of similar levels of environmental protection elsewhere.

This illustrates the importance of where system boundaries are drawn in relation to their permeability: interactions between a subsystem (in this case Europe) and the overall system (the global economy) must be appropriately taken into account in energy system analysis and integration.

Similarly, establishing appropriate system boundaries for life cycle assessments of the environmental impacts of CCS is important. Although CO_2 capture facilities at power plants will reduce direct emissions to air by 85–98%, indirect CO_2 emissions from upstream fuel extraction, preparation, and transport and from downstream transport and storage processes are not typically captured and can be significant (average figures for CO_2 for Europe are around 140 and 80 grams of CO_2 equivalent per kWh for coal and natural gas, respectively), particularly in the context of the intended EU electricity system of 2050 with its nearly zero carbon emissions.

Finally, a generic challenge for CCS is that it requires the integration of four industries that are different in many respects: gas and chemical processing, power generation, transport networks, and geological storage. Each of these has—or must develop—its own culture and levels of risk and return, and each relies on different capital providers.

Discussion

The four EASAC studies examined four very different aspects of modern energy systems, but a trend towards increasing integration emerged as a common theme, bringing opportunities and challenges. A key consideration in all four studies was the need to draw the boundaries of the system appropriately, both for analysis and for planning, management, and regulation of the system. If boundaries are inappropriately drawn, perverse behaviors and outcomes may be induced and important consequences may be missed by the analysis. In some cases, it is important to look beyond the energy system—for example, to the interrelated food and transport systems in the case of biofuels and to regional economic and political systems and aspirations in the case of CSP.

The value of geographical integration is a recurrent driver of EU energy policy—the EU whole is greater than the sum of the member states that are its parts—but requires international harmonization of incentives, regulations, and so on. The underlying premise is that the loss of autonomy by the member states is outweighed by the benefits that wider and more efficient energy markets bring.

Energy system integration generally requires the effective coordination of a wider group of players and the taking of a longer-term view. Coherence is also needed among the various elements of the system—between the markets and the physical infrastructure, for example. EASAC has concluded that the EU does not place enough emphasis on systems approaches in developing its policies and strategies, tending to focus on the development of individual technologies instead. Consequently, EU policies relating to energy at times lack coherence. Similarly, EU energy R&D is still too focused on the development of individual technologies. Such approaches will not be sufficient to achieve EU energy targets.

A better understanding is needed of systems dynamics, transitions, and integration, requiring an interdisciplinary approach. Systems approaches, as well as a deeper understanding of systems dynamics, are needed to unlock the promise of individual technologies and integrate a variety of necessary elements to develop highly efficient and resilient new combinations. Systems approaches must take into account the reception and integration of new technologies into society.

An important example is provided by the EU's target of achieving an essentially decarbonized electricity system by 2050. This will require a radically different system, but not enough work is being done on how this system can be made to work—how the individual components of the new system will be stitched together and how the transition can be achieved, for example. As well as evaluating technologies and undertaking system simulations, a systems approach to analysis of an electricity system dominated by renewable energy sources will have to consider not only technology and infrastructure but also markets, user practices, knowledge infrastructures, policies, regulations, and politics.

Investment in systems research currently accounts for only a small percentage of the EU's energy R&D expenditures and should be increased. The benefit-to-cost ratio of such incremental expenditure on systems research is likely to be substantially higher than for technology development, which typically requires high-cost experimentation and demonstration. A specific recommendation for the SET-Plan is to add an "energy systems" platform. This would provide a mechanism for developing integrated social, economic, and technical perspectives on the issues of EU energy system development.

Europe has rather limited indigenous supplies of fossil energy and more constrained options for its energy system than many other regions of the world, particularly in view of its targets for climate change mitigation. Systems approaches are therefore essential to ensure that best use is made of the resources that are at Europe's disposal and to help guide policies toward solutions with high societal value and good resource utilization. They are also inherently able to address the kinds of questions that are of most concern to policy makers, such as how to achieve security of supply, resilient systems, and so forth.

Conclusions

In modern society, most of our energy is delivered through energy systems that are complex, geographically diverse, and have interactions with other systems and subsystems. One example is the increasing interdependence of the electricity, gas supply, and transport systems. The ways in which these systems are designed and integrated are becoming more and more important. There are many opportunities to improve the overall performance of energy systems with increased levels of integration, but this improvement comes with significant challenges.

Taking a systems approach entails making an interdisciplinary evaluation of the factors determining the behavior of the system as a whole, including the transitions required to achieve target energy outcomes, rather than just focusing on its component parts. Only by developing an understanding of how the system as a whole works and is integrated in society can potential synergies between components be realized in practice and conflicts avoided.

For Further Reading

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Biography

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