Energy Systems Security

Edited by
John G. Voeller

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PREFACE

Adapted from the Wiley Handbook of Science and Technology for Homeland Security.

The topic of homeland security did not begin with the World Trade Center or the IRA or the dissidents of past empires, but began when the concept of a nation versus a tribe took root and allegiance to a people was a choice, not a mandate. The concept of terrorism is part of homeland security but there are other risks to homeland security; such as those that come from Mother Nature or negligence of infrastructure maintenance. Indeed, these factors have much higher probabilities of causing substantial damage and loss of life than any group of terrorists could ever conceive. Hence, the focus here is on situations that put humans at risk and can disrupt and damage infrastructure, businesses, and the environment, and on scientific and technological tools that can assist in detecting, preventing, mitigating, recovering, and repairing the effects of such situations.

The number of science and technology (S&T) related topics that are involved in the physical, cyber and social areas of homeland security includes thousands of specialties in hundreds of disciplines so no single collection could hope to cover even a majority of these. Instead, our intention is to discuss selected topics in ways that will allow readers to acquire basic knowledge and awareness and encourage them to continue developing their understanding of the subjects.

Naturally, in the context of homeland security and counterterrorism, some work has to be classified so as not to “communicate our punches” to our adversaries and this is especially true in a military setting. However, homeland security is concerned with solutions to domestic situations and these must be communicated to officials, law enforcement, and the public. Moreover, having experts speak in an open channel is important for informing researchers, academics, and students so that they can work together and increase our collective knowledge.

There are many ways to address homeland security concerns and needs, and many different disciplines and specialties. An ongoing open conversation among experts which will allow them to connect with others and promote collaboration, shared learning and new relationships is needed. Certainly, creating a forum in which theories, approaches, solutions and implications could be discussed and compared would be beneficial. In addition, reliable sources from which experts and lay persons alike could learn about various facets of homeland security are needed. It is equally important that policy and decision makers get the full picture of how much has been done and how much still needs to be done in related areas.

Even in places that have dealt with terrorism for over a century, there are no strong, cost-effective solutions to some of the most pressing problems. For example, from a distance, we have very limited ability to spot a bomb in a car moving toward a building to allow decision making on whether to destroy or divert the car before it can damage the target. Even simpler, the ability to spot a personnel-borne improvised explosive device (IED) in a crowd coming into a busy venue is still beyond our collective capability. Therefore, the bounding of what we know and don’t know needs to be documented.

Finding additional uses for technologies developed originally to solve a homeland security problem is one of the most important aspects of the economics involved. An inescapable issue in many areas of homeland security S&T, is that even a successful solution when applied to only a small market will likely fail because of insufficient returns. For example, building a few hundred detectors for specific pathogens is likely to fail because of limited demand, or it may never even receive funding in the first place. The solution to this issue is finding multiple uses for such devices. In such a case, a chemical detector for contraband or dangerous materials could be used also to detect specific air pollutants in a building; thus, help allergy sufferers. In this way capabilities developed for homeland security may benefit other, more frequently needed uses, thereby making the invention more viable.

The editors of this work have done a superb job of assembling authors and topics and ensuring good balance between fundamentals and details in the chapters. The authors were asked to contribute material that was instructional, discusses a specific threat and a solution, or provides a case study on different ways a problem could be addressed and what was found to be effective. We wanted new material where possible. The authors have produced valuable content and worked hard to enhance quality and clarity of the chapters. And finally, the Wiley staff has taken on the management of contributors with patience and energy beyond measure.

Senior Editor
John G. Voeller

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COMPARATIVE RISK ASSESSMENT FOR ENERGY SYSTEMS

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1.1 INTRODUCTION

Disasters and accidents occur as a consequence of the exposure of people and their socioeconomic activities to natural and man-made hazards [1–4]. The increase in the numbers and associated consequences of natural disasters and man-made accidents in the last three decades as well as the recurring occurrence of single devastating catastrophes in recent years [5–7] have made the issues of disaster and risk management a top priority at national and international levels. Large loss events cannot be addressed as isolated events anymore because they provide a potential threat to people's health and property, the supply of economic goods and services, and the degradation of ecosystem functions, fauna, and flora. Also, societal vulnerability has further increased because of the steady growth of industrialization, continuing rapid urbanization, the disproportionately high development of coastal and other risk-prone areas, and strong dependency on complex, interrelated infrastructures, constituting a serious challenge to society and its sustainable development [8–12].

Disasters are generally assigned to two principal categories, that is, natural or man-made (anthropogenic or human induced). Natural disasters can be further classified into several distinct groups, including geological (e.g. earthquake and volcano), hydrometeorological (e.g. flood and wind storm), and other (e.g. heat wave, drought, forest fire, and avalanche) disasters. For a more detailed overview, see, for example, the classification schemes used by the Center for Research on the Epidemiology of Disasters (CRED) [13] or international reinsurance companies [6, 7]. Man-made disasters are the result of accidental or intentional human action. Accidental events include transportation accidents, major fires and explosions, releases of chemical and toxic substances, and the

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collapse of technical structures (e.g. buildings, bridges, and dams). Purposed malicious action ranges from vandalism and sabotage to terrorism and war.

In the literature, a large variety of more or less precise definitions of the term *risk* can be found, depending on the field of application, and the specific scope, objective, and boundary conditions of the object under study. In engineering and natural sciences, risk is frequently defined in a quantitative way: *risk (R)* $=$ *probability (p)* $\times$ *consequence (C)*. This definition does not include subjective factors of risk perception and aversion, which can also influence the decision-making process, that is, stakeholders may make trade-offs between quantitative and qualitative risk factors [14]. Quantitative risk assessment is of critical importance in several risk-sensitive industries. Concerning the energy sector, a comprehensive and objective risk evaluation is essential [5] because its complex and interdependent technical systems and facilities comprise critical infrastructure elements to today's information society [11, 15]. Potential accidental events could result in highly undesirable outcomes, calling for an accurate risk assessment and management [16].

In the context of security, risk is often defined as a function of the three variables threat (T), vulnerability (V), and consequence (C): $R = T \times V \times C$. Threat is the measure that a specific accidental or intentional event will take place. Vulnerability is the measure of likelihood that various types of safeguards fail. Consequence is the magnitude of negative effects in the case of an accident or successful attack. This approach allows the identification of areas where high threat levels, extreme vulnerabilities, and high consequences overlap. It is this intersection that causes security concerns. Figure 1.1 provides an overview of the different aspects of each of the three elements.

Although accidents in the energy sector have been shown to form the second largest group (after transportation) of man-made accidents, their level of coverage and completeness is not satisfactory because they are commonly not surveyed and analyzed separately; rather they are implicitly included as one subgroup of technological accidents. In the early 1990s, the Paul Scherrer Institut (PSI) has developed and established the database ENSAD (*en*ergy-related *s*evere *a*ccident *d*atabase) to close this gap [17]. The focus was on severe accidents because they are viewed controversially by the public and in the energy policy debate, although the sum of smaller accidents is substantial. Furthermore, in relative terms, scarce major accidents have a higher probability of being reported and scrutinized than the much more frequent smaller accidents with minor damages [18, 19]. Since its first publication [17], ENSAD has been continuously maintained, updated, and extended in its content, coverage, and scope [5, 20]. Major progress has been achieved within the "China Energy Technology Program (CETP)" [21–23], the European Union (EU) research project on "New Elements for the Assessment of External Costs from Energy Technologies" (NewExt) [5], and a study of natural gas accident risks for the Swiss Gas and Water Industry Association (SVGW) [24]. Most recently, the database was updated and further extended within the Integrated Project "New Energy Externalities Developments for Sustainability" (NEEDS) of the EU 6th Framework Programme.

The comparative assessment of energy-related accident risks has received increased attention in the past few years for several reasons. The general increase in the annual number of accidents and accompanying damages has triggered public awareness. In addition, a number of extremely devastating disasters have amplified this trend, and at the same time the world-leading reinsurance companies have published damage claims that are one of a kind. Furthermore, there are indications that global climate change may lead to future changes in the intensity and frequency of some hazards. In summary, mankind is facing a tremendous challenge to prevent large-scale disasters and/or to mitigate their impacts because they form a potential threat to the cohesion of society and its sustainable development goals.

However, recent experience has shown that it is not sufficient to direct our efforts only to the energy sector itself. On the one hand, energy provides critical inputs in the production of most goods and services, making them a key driver for all kinds of activities in modern society. On the other hand, the functioning of the energy infrastructure is likewise strongly dependent on supporting infrastructures, including availability and replacement of components, transportation, information and telecommunication systems, fuel and water supply, financial services, and so on. In this context, critical infrastructures denote vital systems that are characterized by mutual interdependencies essential for the provision of minimal services of the economy and government [11, 25, 26]. Parallel to the development of concepts for critical infrastructure protection (CIP), the concept of resilience has been applied to accident prevention, disaster management, and sustainable development [27–29]. Finally, the growing threat of international terrorism since the second half of the 1990s has led to the incorporation of CIP and civil emergency planning (CEP) issues into the broader context of homeland security, addressing a number of key aspects of the above-described methodological approaches and concepts [30–33].

This chapter provides a comprehensive, state-of-the-art analysis of severe accident risks in the energy sector. The methodological framework for the comparative assessment

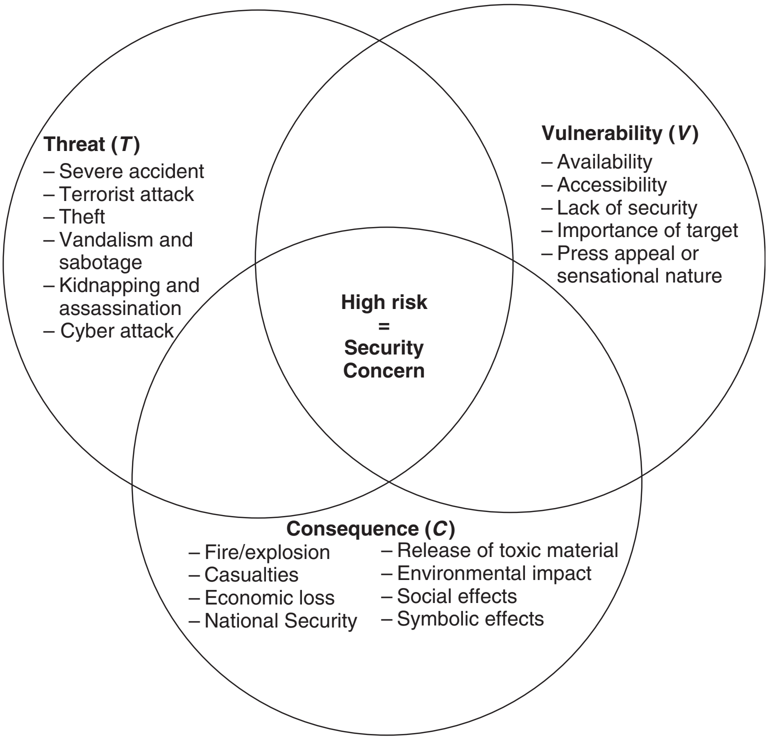

FIGURE 1.1 The Venn diagram for security risk shows the various aspects of the three elements threat, vulnerability, and consequence.

is presented, followed by an overview of the historical experience as represented in ENSAD. Finally, comparisons of energy chains are based on aggregated indicators and frequency–consequence (F–N) curves, two well-established analytical methods.

1.2 ANALYTICAL APPROACH AND METHODOLOGY

1.2.1 Severe Accident Database

In the initial development phase of ENSAD, the requirements and time exposure were examined to build up a severe accident database for the energy sector. These preliminary investigations clearly showed that such a database should not be set up from the scratch, but rather by using existing information sources, because none of the available individual databases offers a fully satisfactory coverage to form alone a basis for the evaluation of severe energy-related accidents. Databases also differ in their scope, information coverage, level of detail, and quality. Therefore, the combination of information from a large variety of sources allows for the most complete compilation of accident records in terms of available information, level of detail, data quality, time period, and geographical coverage. Additionally, commercial databases should also be included to gain access to proprietary data that are not fully contained in publicly available information sources.

Figure 1.2 shows the information sources used to document energy-related accidents included in ENSAD for the years 1969–2000. The four most common sources summed up to 48.5%, followed by seven other sources that cumulatively contributed 22.6%. The remaining more than 170 sources amounted to about 29%. However, many of the sources with small shares were of critical importance because they covered specific energy

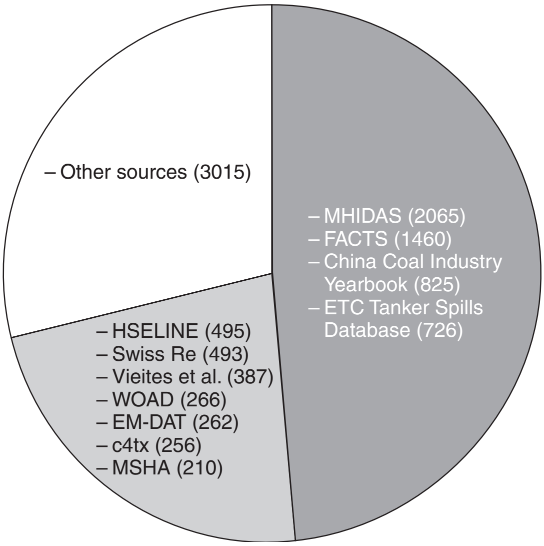

FIGURE 1.2 Contributions of major sources to the total number of energy-related accidents stored in ENSAD for the years 1969–2000. Note that the total number of accidents sums up to more than the 6227 accidents documented in ENSAD because a specific accident may be reported by several sources.

chains and/or countries, were useful to resolve contradicting statements, and provided supplementary information that would otherwise not be available.

A database of the purpose such as ENSAD has to be based on relational database software to keep the amount of redundant information at a minimum level, which is not possible with a traditional spreadsheet approach. In our case, Microsoft Access was chosen because it meets our objectives and needs, and allows flexible programming based on SQL or Visual Basic applications. Its abounding export options facilitate data exchange with statistical software packages, the coupling with geographic information systems (GIS), and integration with other office software, internet, or intranet applications. The complete process of database building and implementation has been described in detail elsewhere [5, 17]; therefore, only an overview of the essential steps is provided here:

1. Selection and survey of relevant information sources. Criteria for acquisition include that retrieved data are of sufficient quality in terms of detail and accuracy.
2. Raw information is merged, harmonized, checked for inconsistencies, and verified before records are included in ENSAD.
3. Energy-related accidents are assigned to a specific energy chain and to a specific step within the selected chain. Information on date of occurrence, geographic location and site specification, country-specific attributes, accident type classification, technological characteristics, damage assessment, accident analysis, and verbal description is then collected and entered in ENSAD.
4. The database content of ENSAD is once more cross-checked to keep data errors at the lowest feasible level.
5. Comparative evaluations are then carried out on the basis of customized ENSAD queries.

1.2.2 Severe Accident Definition

In the literature, no unambiguous definition of the term *severe accident* can be found. Differences concern the actual damage types considered (e.g. fatalities, injured persons, evacuees, or economic costs), use of loose categories such as “people affected”, and differences in damage thresholds to distinguish severe from smaller accidents.

This can be illustrated by the following examples. The “Worldwide Offshore Accident Database (WOAD)” of the Det Norske Veritas [34] considers an accident as severe or major, if more than one fatality occurred or if the damaged unit (e.g. oil platform, drill ship, or drill barge) experienced total loss. Glickman and Terry [35] define a significant accident for technological hazard, if it resulted in at least five fatalities or if it involved the release of a chemical, petroleum product, hazardous waste, or other hazardous material. The SIGMA publication series of Swiss Re Company [7] does not use the term *severe accidents*, but rather refers to catastrophic events.

The database of ENSAD uses seven criteria to distinguish between severe and smaller accidents. Whenever an accident is characterized by one or more of the following consequences, it is considered to be severe:

1. at least five fatalities;
2. at least 10 injured;
3. at least 200 evacuees;

4. extensive ban on consumption of food;
5. releases of hydrocarbons exceeding 10,000 (metric) tones (t);
6. enforced clean-up of land and water over an area of at least 25 km^2; or
7. economic loss of at least 5 million USD (2000).[1]

Generally, fatality data is most reliable, accurate, and complete, whereas in the case of injured or evacuated persons, details on the severity of an injury or the duration of an evacuation are frequently not clearly indicated. The estimation of precise values for economic loss is often difficult because different sources of information report various types of economic damages (e.g. insured vs. total loss), depending on their specific scope (e.g. insurance company vs. disaster recovery organizations). The other consequence indicators are either only relevant for specific energy chains or ENSAD contains very few entries with sufficiently detailed information. Therefore, ENSAD-based results presented here are focused on the number of fatalities.

1.2.3 Consideration of Full Energy Chains

The ENSAD database allows carrying out comprehensive analyses of accident risks that are not limited to power plants but cover full energy chains. Such a broader perspective is essential because for the fossil chains, accidents at power plants play a minor role compared to the other chain stages, that is analyses based on only power plants would radically underestimate the real situation [17].

In general, an energy chain may comprise the following stages: exploration, extraction, transports, storage, power and/or heat generation, waste treatment, and disposal. However, one should be aware that not all these stages are applicable to every energy chain. Table 1.1 gives an overview of distinct stages for the major fossil (coal, oil, natural gas, and liquefied petroleum gas (LPG)), hydro, and nuclear chains.

1.2.4 Normalization and Allocation of Damages

Comparisons of the various energy chains were based on data normalized to the unit of electricity production. For fossil energy chains, the thermal energy was converted to an equivalent electrical output using a generic efficiency factor of 0.35. For nuclear- and hydropower, the normalization is straightforward since in both cases the generated product is electrical energy. The gigawatt-electric-year ($\text{GW}_\text{e}\text{yr}$) was chosen because large individual plants have capacities in the neighborhood of 1 GW of electrical output (GW_e). This makes the $\text{GW}_\text{e}\text{yr}$ a natural unit to use in discussions of total electricity production.

Results are provided separately for OECD (Organization for Economic Co-operation and Development) and non-OECD countries because of large differences in levels of technological development and safety performance. This distinction is also meaningful because of the substantial differences in management, regulatory frameworks, and general safety culture between these two groups of countries [5, 17, 36, 37]. Analyses were complemented by separate calculations for the Chinese coal chain. In the case of China, coal chain data were analyzed only for the years 1994–1999 when data from the China

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[1] Different currencies were all converted to USD values. To take account of inflation, specific amounts were extrapolated using the US Consumer Price Index (CPI) to obtain year 2000 values.

TABLE 1.1 Chain Stages of Major Energy Chains. Based on Hirschberg et al. [17]

	Coal	Oil	Natural Gas	LPG	Nuclear	Hydro
Exploration	Exploration	Exploration	Exploration	-	Exploration	
Extraction	Mining and Coal Preparation	Extraction	Extraction and Processing	-	Mining/Milling	
Transport	Transport to Conversion Plant	Transport to Refinery (Long Distance Transport)	Long Distance Transport (Pipeline)	-	Transport	
Processing	Conversion plant	Refinery		• Refinery • Natural gas processing Plant	Upstream Processing	
Transport	Transport	Regional Distribution	Distribution: - Long Dist. - Regional - Local	Distribution: - Long Dist. - Regional - Local	Transport	
Power/Heat Generation	Power Plant/Heating Plant	Power Plant/Heating Plant	Power Plant/Heating Plant	Heating Plant	Power Plant	Power Plant
Transport					Transport to Reprocessing Plant	
Processing					Reprocessing	
Waste Treatment	Waste Treatment				Waste Treatment	
Waste Disposal	Waste Disposal				Waste Disposal	

Coal Industry Yearbook were available, indicating that previous years were subject to substantial underreporting [21–23].

A difficulty that arises in comparative studies with aggregated normalized severe accident records is that a large number of severe accidents occur in non-OECD countries at stages in the energy chain relevant for the export to OECD countries. This can be incorporated in the calculations by adding the appropriate share of the consequences of accidents that occurred at such energy chain stages in non-OECD countries to the damages that physically occurred in OECD countries, that is, OECD countries "import" fatalities. The net amounts of energy carriers imported to OECD countries from non-OECD countries form the basis for this allocation procedure, which has been described in detail in Hirschberg et al. [17]. It has been shown that OECD countries import from non-OECD countries a large fraction of their total consumption of crude oil and LPG, a small fraction of natural gas, and a negligible fraction of coal [5]. Aggregated indicators with allocation are particularly useful within a sustainable development perspective because they assume that the industrial OECD countries should bear a certain share of these damages.

1.2.5 Simplified Probabilistic Safety Assessment for Nuclear Power Plants

The simplified approach used by us in comparative risk studies is described in detail in [22, 23]. It builds on adapting plant-specific source terms from publicly available Level II probabilistic safety assessment (PSA) and combining them with a simplified assessment of off-site consequences resulting from hypothetical nuclear accidents. The basis for the methodology is calculations carried out using MACCS2 consequence code for the same light water reactor (LWR) plant and for two hypothetical accidents, one with early containment rupture and the other with a late vented release. Data for two different sites are used for the dispersion and dose calculations, the first a European continental site with relatively large population density in the vicinity of the plant, and the other a US site with relatively low population density within the first 10 km.

Early fatalities can be extrapolated from one site to another from the ratio of population within 8–10 km. This is because the radioactive content in a passing cloud is effectively dispersed over a very large volume very quickly (the MACCS2 code uses a Gaussian dispersion model), and the MACCS2 calculations show that mortality distance does not exceed 20 km under the worst possible weather conditions (i.e. with very small probability).

Delayed cancer deaths are found to be strongly correlated with the total population within 80–120 km. The MACCS2 calculations show that only a small background of delayed fatalities may occur beyond this distance. This is due to cloud dispersion and dilution of activities, since the dose must be incurred via inhalation or submersion in the passing cloud. Cancer deaths occurring from ingestion (late deaths) are found to be correlated with the total population around the site considered. For both the sites, a maximum distance of 800 km was considered; therefore, late deaths are considered proportional to the ratio of populations within 800 km.

Finally, land contamination is assumed to be correlated with the ratio of land fractions to 120 km, even though the correlation was found to be weaker than the ones found for health effects. A distance of 120 km is assumed for this type of calculations, because the MACCS2 results show that the maximum distance where land can be severely contaminated does not exceed 120 km for any of the radionuclide groups.

In conclusion, off-site consequences may be calculated approximately using activity of releases, as provided by Level II PSAs for the relevant source terms and the ratios discussed above.

1.3 OVERVIEW AND CONTENTS OF ENSAD

Currently, 18,706 accident records are stored in the ENSAD database, of which 88.4% fall in the period between 1969 and 2000. Within this period, 6995 accidents were considered severe because they resulted in at least five fatalities. Of these accidents, 39.5% were natural disasters and the other 4233 were man-made accidents. The latter can be further divided into energy-related accidents (1870 or 44.2%) and other man-made accidents (2363 or 55.8%). Figure 1.3 shows fatalities in all categories of severe (≥5 fatalities) man-made accidents and natural disasters from 1969 to 2000, totaling to about 3.4 million fatalities. Of these victims, more than 90% were due to natural catastrophes and about 10% were due to severe man-made accidents; 37% of the latter were killed in energy-related accidents.

The largest natural disasters were a storm and flood catastrophe in Bangladesh in 1970 (300,000 fatalities), the Tangshan earthquake in China in 1976 (290,000), and a drought and civil strife in Sudan in 1983 (250,000). In contrast, the largest man-made accidents resulted in fatalities one to two orders of magnitude lower. The top-ranked energy-related accidents include the Banqiao/Shimantan dam failure in China in 1975 (26,000 fatalities), the collision of the tanker "Victor" with the Ferry "Dona Paz" off the Philippines in 1987 (4386), and a tank truck collision with another vehicle in the Salang

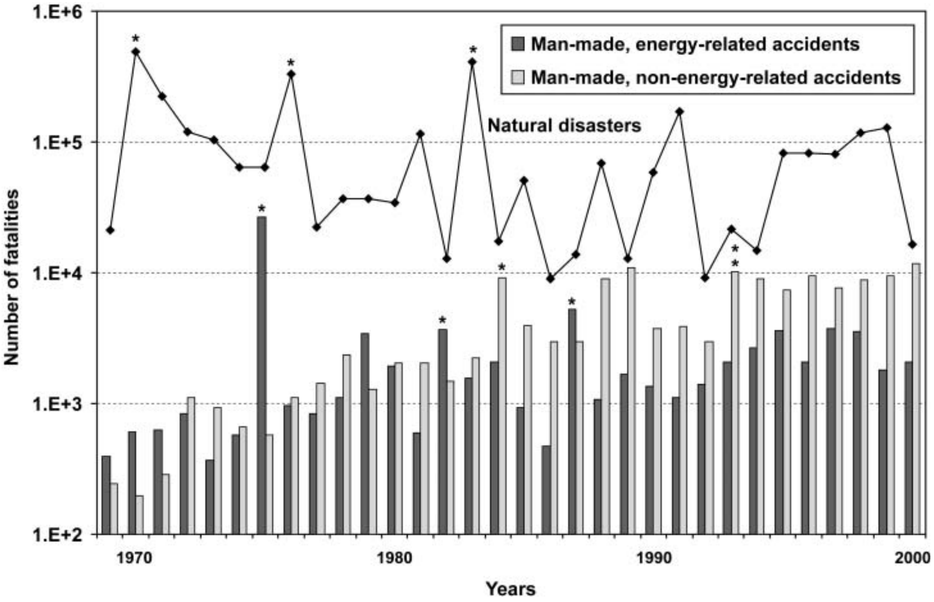


FIGURE 1.3 Number of fatalities for severe (≥5 fatalities) accidents that occurred due to natural disasters and man-made accidents in the period 1969–2000. Years marked by an asterisk indicate the three most deadly accidents per category, which are also described in the text.

TABLE 1.2 Summary of Numbers (acc) and Fatalities (fat) of Severe (≥5 fatalities) Accidents for the Different Energy Chains and Country Groups for the Years 1969–2000

	OECD		Non-OECD		Worldwide	
Energy chain	Acc	Fat	Acc	Fat	Acc	Fat
Coal	75	2259	102 1044 819[a]	4831 18,017 11,334[a]	1221	25,107
Oil	165	3713	232	16,505	397	20,218
Natural gas	90	1043	45	1000	135	2043
LPG	59	1905	46	2016	105	3921
Hydro	1	14	10	29,924[b]	11	29,938
Nuclear	0	0	1	31[c]	1	31
Total	390	8934	1480	72,324	1870	81,258

[a] Three values (first to third line) are given for the coal chain in non-OECD countries: non-OECD without China, China 1969–2000, and China 1994–1999 (see text).

[b] Banqiao/Shimantan dam failures together caused 26,000 fatalities.

[c] Only immediate fatalities, see text for latent fatalities.

tunnel in Afghanistan's Parvan province in 1982 (2700). Furthermore, 9 out of the 10 most deadly accidents in the energy sector occurred in non-OECD countries, and were attributable to oil and hydro chains. Large nonenergy-related severe accidents include the accident at a pesticide plant in Bhopal in India in 1984 (5000 fatalities), the sinking of the ferry "Neptune" near the coast of Haiti in 1993 (1800), and the failure of the Gouhou dam (primary purpose: irrigation and water supply) in China in 1993 (1250).

For the period 1969–2000, the ENSAD database comprises 1870 severe accidents attributable to the energy sector, with a corresponding total of 81,258 fatalities (Table 1.2). The coal chain accounted for 65.3% of all accidents, with oil a distant second at 21.2%. Contributions by the natural gas (7.2%) and LPG (5.6%) chains were much less, while both hydro and nuclear account for less than 1% each. This dominance of coal chain accidents is fully attributable to the release of detailed accident statistics by China's coal industry, data that were not previously publicly available [21–23]. Altogether, 819 of the 1044 accidents collected for the Chinese coal chain occurred in the years 1994–1999, implying substantial underreporting prior to the release of the annual editions of the China Coal Industry Yearbook. Fatalities were clearly dominated by the Banqiao/Shimantan dam failures, which together resulted in 26,000 deaths. As a consequence, the hydro chain accounts for 36.8% of all fatalities. Among the fossil chains, coal accounted for the most fatalities, followed by oil, LPG, and natural gas.

Cumulated numbers of accidents for the different fossil energy chains were plotted on a world map for each country to visualize spatial distribution patterns and to identify accident hotspots (Figure 1.4). Additionally, total fatalities and chain contributions are shown for the top 10 countries in terms of fatalities, and for each energy chain the most deadly accident is indicated. Among the countries with highest death tolls, seven of them were non-OECD countries and only three belonged to the OECD countries. However, Mexico and South Korea gained OECD membership only in the mid 1990s (1994 and 1996, respectively), whereas United States has been a member since OECD's foundation in 1961. China was the most accident-prone country with 19,141 fatalities, of which

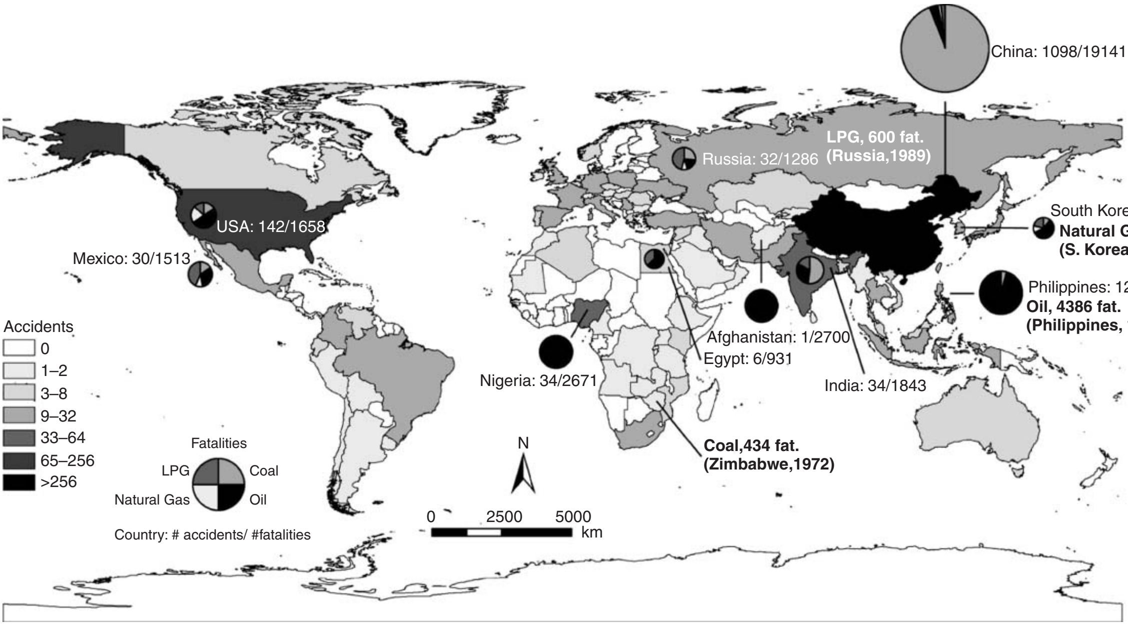


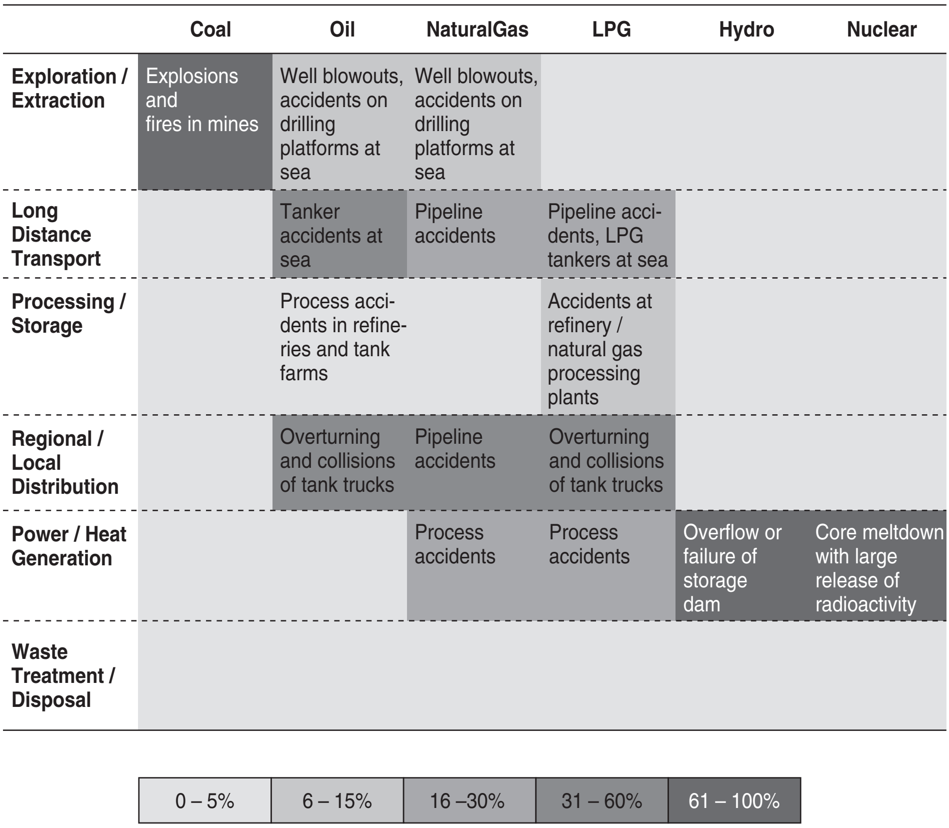
FIGURE 1.4 Individual countries are shaded according to their total number of severe accidents in fossil energy chains (coal, oil, natural gas, and LPG) for the period 1969–2000. Pie charts show the contributions per chain for the top 10 countries in terms of fatalities. The most deadly accident for each chain is also indicated.

18,017 fatalities occurred in 1044 accidents attributable to the coal chain, but only nine of these resulted in 100 or more fatalities (Table 1.2). In contrast, the cumulated fatalities of the Philippines, Afghanistan, Nigeria, India, Mexico, Russia, South Korea, and Egypt were strongly influenced by a few very large accidents that contributed a substantial share of the total [36, 37]. United States exhibited a distinctly different pattern compared to the other countries with no extremely large accidents (only 3 out of 142 with more than 50 fatalities), and over 70% of accidents and associated fatalities taking place in the oil and gas chains.

1.4 COMPARATIVE ANALYSIS OF ENERGY CHAINS

The majority of accidents in fossil energy chains do not occur in power plants, but rather in other stages in the energy chains (Table 1.3). Over 95% of the victims in the coal chain lose their lives in mines, primarily due to gas explosions. With oil, the transportation to the refinery and regional distribution is the most accident-prone stage; most frequent are tanker accidents at sea and road accidents involving tank trucks. Transportation is also a weak stage in the natural gas chain, which is dominated by pipeline accidents

TABLE 1.3 Relative Share of Accidental Fatalities in the Stages of Different Energy Chains



	Coal	Oil	NaturalGas	LPG	Hydro	Nuclear
Exploration / Extraction	Explosions and fires in mines	Well blowouts, accidents on drilling platforms at sea	Well blowouts, accidents on drilling platforms at sea			
Long Distance Transport		Tanker accidents at sea	Pipeline accidents	Pipeline accidents, LPG tankers at sea		
Processing / Storage		Process accidents in refineries and tank farms		Accidents at refinery / natural gas processing plants		
Regional / Local Distribution		Overturning and collisions of tank trucks	Pipeline accidents	Overturning and collisions of tank trucks		
Power / Heat Generation			Process accidents	Process accidents	Overflow or failure of storage dam	Core meltdown with large release of radioactivity
Waste Treatment / Disposal						

0 – 5%	6 – 15%	16 –30%	31 – 60%	61 – 100%

in transmission (long distance) and distribution (regional/local) networks. In the LPG chain, transportation accidents are most prominent too, particularly in regional and local distribution. In contrast, hydropower and nuclear power accidents occur only near the area of the storage dam or reservoir and the plant site, respectively. While coal chain victims are almost exclusively work related, gas and oil accidents involve a significant number of innocent bystanders as victims. If a storage dam breaks, then the general populace is almost exclusively affected, with the exception of the dam operators. Nuclear plant accidents may also lead to immediate fatalities, but here the deaths are dominated by latent fatalities (compare Sections 3.1 and 3.2) due to eventual cases of cancer.

1.4.1 Aggregated Indicators

Aggregated fatality rates of severe ($\geq$5 fatalities) accidents are reported only for immediate fatalities, whereas the significance of latent fatalities in the case of the nuclear chain is discussed in Section 3.2. Damage rates differed substantially among energy chains and country groups, with OECD countries generally showing significantly lower fatality rates than non-OECD countries (Table 1.4). Among the fossil chains, natural gas has the best performance, followed by oil and coal, whereas the value for LPG is one order of magnitude worse. The lowest fatality values occur for western style nuclear and hydropower plants, whereas dam failures in non-OECD countries may lead to thousands of victims in the downstream population. Additionally, Table 1.4 also displays a full allocation of damages for fossil energy chains on the basis of imports and exports (Section 1.4) because a large number of severe accidents in non-OECD countries are related to energy exports to the OECD countries. Severe fatality rates for the oil and LPG chains exhibited the most distinct increase for OECD countries and decrease for non-OECD countries compared to the rates without allocation, whereas differences for coal and natural gas chains were distinctly less. Within the framework of sustainable development, it could be argued that the highly industrialized OECD countries should assume a certain share of these damages.

TABLE 1.4 Aggregated Fatality Rates for Full Energy Chains Based on Historical Experience of Severe Accidents ($\geq$5 immediate fatalities) in OECD and Non-OECD Countries for the Period 1969–2000, Except for China 1994–1999 (compare text). Allocated Values Incorporate Imports and Exports between OECD and Non-OECD

	No Allocation/With Allocation [fatalities/$\mathrm{GW_e}$yr]	
	OECD	Non-OECD
Coal	0.157/0.163	0.597/0.589 6.169[a]
Oil	0.132/0.390	0.897/0.502
Natural gas	0.085/0.097	0.111/0.096
LPG	1.957/3.317	14.896/5.112
Hydro	0.003	10.285 1.349[b]
Nuclear	—	0.048[c]

[a] First line: OECD without China; second line: China for the period 1994–1999.

[b] Chinese dam failures of Banqiao/Shimantan with a total of 26,000 fatalities are excluded.

[c] Only immediate fatalities of Chernobyl accident; see text for latent fatalities.

1.4.2 Frequency–Consequence Curves

Figure 1.5 provides *F–N* curves for severe (≥5 fatalities) accidents in OECD and non-OECD countries, including allocated curves. For fossil chains in OECD countries, natural gas has the lowest frequency, coal and oil are intermediate, and LPG has the highest frequency, whereas hydro and nuclear chains perform significantly better. Maximum consequences are negligible for hydro, followed distantly by natural gas (109 fatalities),

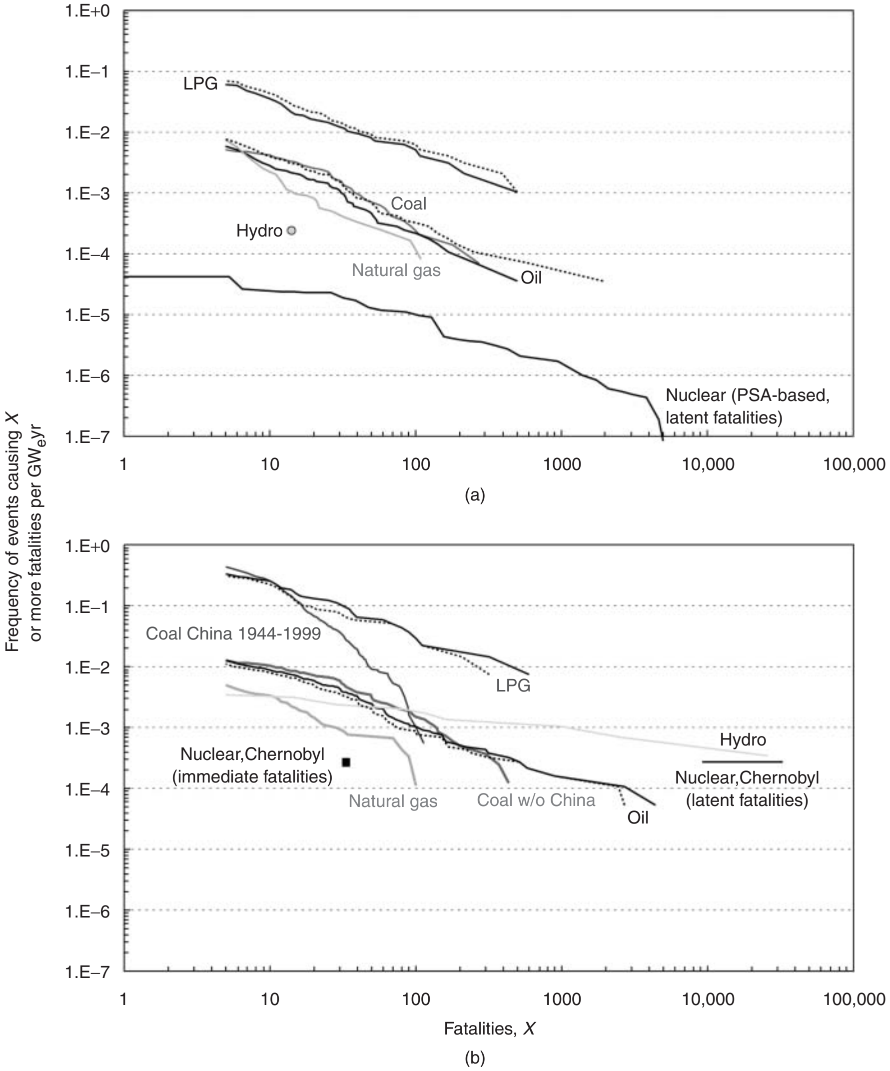


FIGURE 1.5 Comparison of frequency–consequence curves for full energy chains based on historical experience of severe accidents in (a) OECD and (b) non-OECD countries for the period 1969–2000, except for China 1994–1999 (compare text). Dashed lines denote *F–N* curves based on allocated values, that is, taking into account imports and exports between OECD and non-OECD countries. For natural gas, allocated curves are not shown as they are almost identical to nonallocated ones.

and the other fossil chains have maxima between 2.5 and 4.5 times greater than natural gas. Concerning allocated $F-N$ curves, those for natural gas are practically identical (not shown in figure), the allocated curve for LPG exhibits higher frequencies at corresponding numbers of fatalities, whereas for the oil chain maximum consequences increase by a factor of about 3.8. This is fully attributable to the extremely deadly accident in the Philippines with 4386 fatalities already discussed before.

Non-OECD countries showed a comparable ranking as for OECD countries, except for the Chinese coal chain that performed significantly worse. However, the frequencies at corresponding numbers of fatalities were generally higher for non-OECD countries compared to OECD countries. Additionally, values for maximum consequences were one order of magnitude higher for the oil chain (4386 fatalities) compared to OECD countries, and the Chinese dam failure of Banqiao/Shimantan with 26,000 fatalities is by far the most deadly accident in terms of immediate fatalities. Concerning allocated $F-N$ curves, the oil and LPG chains have clearly lower maxima, whereas curves for natural gas are again almost identical.

For nuclear energy, immediate fatalities play a minor role, whereas latent fatalities clearly dominate. Therefore, total fatalities are split into the following categories: early (immediate) fatalities that occur shortly after exposure and latent fatalities that include all potential deaths occurring within 70 years from the radioactive release. For details see Burgherr et al. [5] and Hirschberg et al. [17]. Accident frequencies causing actual damage external to the plant associated with the nuclear chain (Chernobyl) are relatively low, but the maximum credible consequences may be very large due to the dominance of latent fatalities. According to Hirschberg et al. [17], estimated latent fatalities due to delayed cancers range from about 9000 (based on dose cutoff) to 33,000 (entire northern hemisphere with no dose cutoff) over the next 70 years. In 2005, a study by the “Chernobyl Forum”—a consortium of several United Nations organizations, the World Bank and the Russian, Belarus and Ukrainian governments—estimated that in the areas with high contamination, up to 4000 people could eventually die due to radiation doses from the Chernobyl accident, most of them among the so called liquidators [38]. Because of the more limited area considered, this value is substantially lower than the PSI values previously mentioned. The upper range in PSI’s estimate is conservative (as intended) because it was not limited to the most contaminated areas. Finally, one should be aware that no dependable statistics can be determined from this single, severe accident. The Chernobyl accident data also cannot be transferred to Western plants, because they use a very different technology. For realistic calculations, it is necessary to use PSA (Figure 1.5).

1.5 CONCLUSIONS AND RECOMMENDATIONS

1.5.1 Comparative Aspects

- The ENSAD database provides comprehensive accident data for the objective and quantitative analysis of specific technical aspects and the comparative assessment of severe accident risks in the energy sector. However, it is in the nature of the topic that new accidents continuously occur; therefore, the ENSAD database needs to be maintained, updated, and extended to keep up with the growing historical experience and to provide state-of-the-art estimates of risk indicators.

- Energy-related accident risks in non-OECD countries are distinctly higher than in OECD countries; reflected by aggregated indicators as well as $F-N$ curves.
- The most accident-prone energy chain stages are upstream stages (i.e. extraction, refining, and transportation) in fossil energy chains, and hydropower in the less developed (non-OECD) countries.
- Expected fatality rates are lowest for Western hydropower and nuclear power plants. However, the maximum consequences can be very high. The associated risk valuation is subject to stakeholder value judgments and can be pursued in multicriteria decision analysis [39, 40].
- PSA perspective on severe accident risks is particularly important for energy chains whose risks are dominated by power plants, the historical experience of accidents is scarce, or its applicability is highly restricted. These conditions are valid for most Western hydro- and nuclear power plants.

1.5.2 Selected Future Developments

- Estimation of risk indicators for *future technologies* based on extrapolations of currently operating systems. This type of analysis has been introduced in the NEEDS Project of the EU 6th Framework Programme, and is further developed, systematized, and extended in several upcoming projects.
- Further advancement of the *simplified PSA approach* to establish a broader reference database for site-specific risk indicators for advanced nuclear designs has been initiated.
- Broader and *systematic evaluation of smaller accidents* in the fossil chains, as it has already been undertaken for natural gas [24]. Such an effort, however, requires access to the relevant raw data that are often subject to proprietary use.
- Qualitative analysis of *indirect impacts of accidents* on the energy sector. Besides the purely physical effects of severe accidents, a variety of indirect effects can occur, including environmental concerns (e.g. oil spills), acceptance problems of specific technologies due to extremely large maximum credible consequences or high accident frequencies, potential social conflicts among stakeholders (e.g. oil companies and local tribe communities in developing countries), and so on.
- Enhanced coupling of the ENSAD database with *Geographic Information System* (ArcGIS) together with multivariate statistical analyses to analyze spatial patterns across hierarchical scales.

REFERENCES

1. Dao, H., and Peduzzi, P. (2004). Global evaluation of human risk and vulnerability to natural hazards. In *Proceedings from: EnviroInfo 2004 Conference*, Editions du Tricorne, Geneva, Vol. 1.
2. Dilley, M. (2006). Setting priorities: global patterns of disaster risk. *Philos. Trans. R. Soc. A* **364**, 2217–2229.
3. Lerner-Lam, A. (2007). Assessing global exposure to natural hazards: progress and future trends. *Environ. Hazards* **7**, 10–19.

4. UNDP (2004). *Reducing Disaster Risk: A Challenge for Development*, UNDP Bureau for Crisis Prevention and Recovery, New York.
5. Burgherr, P., Hirschberg, S., Hunt, A., and Ortiz, R. A. (2004). *Severe accidents in the energy sector. Final Report to the European Commission of the EU 5th Framework Programme "New Elements for the Assessment of External Costs from Energy Technologies" (NewExt)*, DG Research, Technological Development and Demonstration (RTD),Brussels, Online-Version under: http://www.ier.uni-stuttgart.de/public/de/organisation/abt/tfu/projekte/newext/newext_final.pdf.
6. Munich, R. (2007). *Topics Geo: Natural Catastrophes 2006—Analyses, Assessments, Positions*, Munich Re Group, Munich.
7. Swiss, R. (2008). *Natural Catastrophes and Man-made Disasters in 2007: High Losses in Europe. Sigma No. 1/2008*, Swiss Reinsurance Company, Zurich.
8. Barnett, J. (2003). Security and climate change. *Glob. Environ. Change* **13**, 7–17.
9. Beniston, M. (2007). Linking extreme climate events and economic impacts: examples from the Swiss Alps. *Energy Policy* **35**, 5384–5392.
10. Dilley, M., Chen, R. S., Deichmann, U., Lerner-Lam, A. L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B., and Yetman, G. (2005). *Natural Disaster Hotspots. A Global Risk Analysis*, Disaster Risk Management Series, No. 5. The World Bank, Hazard Management Unit, Washington, DC.
11. Rinaldi, S. M., Peerenboom, J. P., and Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Syst. Mag*. **21**(6), 11–25.
12. WEF (2008). *Global Risks 2008—A Global Risk Network Report*, World Economic Forum, Cologny/Geneva.
13. EM-DAT (2008). *The OFDA/CRED International Disaster Database*, Retrieved from http://www.em-dat.net (January 2008).
14. Gregory, R., and Lichtenstein, S. (1994). A hint of risk: tradeoffs between quantitative and qualitative risk factors. *Risk Anal*. **14**(2), 199–206.
15. Gheorghe, A. V., Masera, M., Weijnen, M., and De Vries, L. J. (2006). *Critical infrastructures at risk. Securing the European Electric Power System*, *Series: Topics in Safety, Risk, Reliability and Quality*, Springer, Dordrecht, Vol. 9.
16. Flyvbjerg, B. (2006). From Nobel Prize to project management: getting risks right. *Proj. Manage. J*. **37**(3), 5–15.
17. Hirschberg, S., Spiekerman, G., and Dones, R. (1998). *Severe Accidents in the Energy Sector*, 1st ed., Paul Scherrer Institut, Villigen PSI, PSI Report No. 98-16.
18. Marshall, V. C. (1987). *Major Chemical Hazards*, Ellis Horwood Limited, Chichester.
19. van Beek, P. C. (1994). *Presentation of FACTS, A Database for Industrial Safety*, AC-Laboratorium, Spiez.
20. Hirschberg, S., Burgherr, P., Spiekerman, G., and Dones, R. (2004). Severe accidents in the energy sector: comparative perspective. *J. Hazard. Mater*. **111**(1–3), 57–65.
21. Burgherr, P., and Hirschberg, S. (2007). Assessment of severe accident risks in the Chinese coal chain. *Int. J. Risk Assess. Manage*. **7**(8), 1157–1175.
22. Hirschberg, S., Burgherr, P., Spiekerman, G., Cazzoli, E., Vitazek, J., and Cheng, L. (2003). Assessment of severe accident risks. In *Integrated Assessment of Sustainable Energy Systems in China. The China Energy Technology Program—A Framework for Decision Support in the Electric Sector of Shandong Province*, *Alliance for Global Sustainability Series*, B. Eliasson, and Y. Y. Lee, Eds. Kluwer Academic Publishers, Amsterdam, Vol. 4, pp. 587–660.
23. Hirschberg, S., Burgherr, P., Spiekerman, G., Cazzoli, E., Vitazek, J., and Cheng, L. (2003). *Comparative Assessment of Severe Accidents in the Chinese Energy Sector*, Paul Scherrer Institut, Villigen PSI, *PSI Report No. 03-04*.

24. Burgherr, P., and Hirschberg, S. (2005). *Comparative Assessment of Natural Gas Accident Risks*, Paul Scherrer Institut, Villigen PSI, PSI Report No. 05-01.
25. IRGC Policy Brief (2007). *Managing and Reducing Social Vulnerabilities from Coupled Critical Infrastructures*, International Risk Governance Council, Geneva.
26. Jones, A. (2007). Critical infrastructure protection. *Comput. Fraud Secur*. **2007**(4), 11–15.
27. Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra* **19**(4), 733–752.
28. Hollnagel, E. (2006). Resilience—the challenge of the unstable. In *Resilience Engineering: Concepts and Precepts*, E. Hollnagel, D. D. Woods, and N. Leveson, Eds. Ashgate, Aldershot.
29. Perrings, C. (2006). Resilience and sustainable development. *Environ. Dev. Econ*. **11**, 417–427.
30. Moteff, J., and Parfomak, P. (2004). *Critical Infrastructure and Key Assets: Definition and Identification*, Congressional Research Service (CRS), The Library of Congress, Washington, DC.
31. The White House (2003). *The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets*, The White House, Washington, DC.
32. The White House (2007). *National Strategy for Homeland Security*, Homeland Security Council, Washington, DC.
33. Willis, H. H., LaTourrette, T., Kelly, T. K., Hickey, S., and Neill, S. (2007). *Terrorism Risk Modeling for Intelligence Analysis and Infrastructure Protection. RAND Center for Terrorism Risk Management Policy for the Department of Homeland Security*, RAND Corporation, Santa Monica, CA.
34. DNV (1999). *Worldwide Offshore Accident Databank (WOAD)*, WOAD statistical report 1998. Det Norske Veritas AS, Hovik.
35. Glickman, T., and Terry, K. (1994). *Using the News to Develop a World-wide Database of Hazardous Events*, Center for Risk Management, Resources for the Future, Washington, DC.
36. Burgherr, P., and Hirschberg, S. (2008). Severe accident risks in fossil energy chains: a comparative analysis. *Energy* **33**(4), 538–553.
37. Burgherr, P., and Hirschberg, S. (in press) A comparative analysis of accident risks in fossil, hydro and nuclear energy chains. *Hum. Ecol. Risk Assess*. **14**(5), 947–973.
38. Chernobyl Forum (IAEA, W, UNDP, FAO, UNEP, UN-OCHA, UNSCEAR, World Bank, Governments of Belarus, the Russian Federation and Ukraine) (2005). *Chernobyl's Legacy: Health, Environmental and Socio-economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine. The Chernobyl Forum: 2003–2005,* Second revised version, IAEA, Vienna.
39. Hirschberg, S., Dones, R., and Gantner, U. (2000).Use of external cost assessment and multi-criteria decision analysis for comparative evaluation of options for electricity supply. In *Proceedings of the "5th International Conference on Probabilistic Safety Assessment and Management PSAM 5", 27 Nov–1 Dec 2000, Osaka, Japan*, Universal Academy Press, Tokyo.
40. Hirschberg, S., Dones, R., Heck, T., Burgherr, P., Schenler, W., and Bauer, C. (2004). *Sustainability of Electricity Supply Technologies Under German Conditions: A Comparative Evaluation*, Paul Scherrer Institut, Villigen PSI, *PSI-Report No. 04-15*.

FURTHER READING

Ale, B. J. M., and Uitdehaag, P. A. M. (1999). *Guidelines for Quantitative Risk Analysis*, (CPR18E) RIVM. SDU-Publishers, The Hague.

Bajpai, S., and Gupta, J. P. (2007). Securing oil and gas infrastructure. *J. Petrol. Sci. Eng*. **55**, 174–186.

Duffey, R. B., and Saull, J. W. (2003). *Know the Risk. Learning from Errors and Accidents: Safety and Risk in Today's Technology*, Butterworth-Heinemann, Burlington, MA.

Eliasson, B., and Lee, Y. Y. (eds.) (2003). Integrated assessment of sustainable energy systems in China. The China Energy Technology Program—A framework for decision support in the electric sector of Shandong province. In *Alliance for Global Sustainability Bookseries Science and Technology: Tools for Sustainable Development*, J. M. Kauffmann, Ed. Kluwer Academic Publishers, Dordrecht / Boston / London, Vol. 4.

Jonkman, S. N., van Gelder, P. H. A. J. M., and Vrijling, J. K. (2003). An overview of quantitative risk measures for loss of life and economic damage. *J. Hazard. Mater*. **99**, 1–30.

Konstandinidou, M., Nivolianitou, Z., Markatos, N., and Kiranoudis, C. (2006). Statistical analysis of incidents reported in the Greek petrochemical industry for the period 1997–2003. *J. Hazard. Mater*., **135**(1–3), 1–9.

Swiss, R. (2002). *Terrorism—Dealing with the New Spectre (Focus Report)*, Swiss Reinsurance Company, Zurich.

Wilson, R., and Crouch, E. A. C. (2001). *Risk-benefit Analysis*, Harvard University Press, Cambridge, MA.

2

LARGE-SCALE ELECTRICITY TRANSMISSION GRIDS: LESSONS LEARNED FROM THE EUROPEAN ELECTRICITY BLACKOUTS

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2.1 INTRODUCTION

Electricity as the most versatile form of energy is the commodity of civilization, which has become something without which modern life is unthinkable. It is not a primary form of energy, but rather a secondary one, which has to be converted from various primary forms. The locations where these are available may be at distances to those where they are consumed; for example, hydraulic sources or technical constraints may require distant placements of generating stations, although primary sources would allow their site anywhere. Further, electricity requires a transport by conductors or better by transmission lines. Thus, transmission is a basic means for providing electricity to consumers. Since the transportation loss is a function of the current, the transportation over long distances is done at high voltages as high voltages allow low currents, which produce low losses. Single transmission lines are not enough as they do not guarantee enough reserves. Hence, the practice has led to the formation of interconnected transmission networks, which provide reserves, contribute to the economy of the operation and equalize between deficiencies and surplus.

The interconnection, however, implies the propagation of disturbances over wide areas. Hence, deficiencies or surplus of power are felt in the overall system. In extreme condition, a disturbance with all possible internal corrections may evolve to a blackout or near blackout as experienced in recent years in the European interconnected system. There are various causes for blackouts, such as technical, conceptual, due to misunderstanding of phenomena, or simply due to human error.

Energy Systems Security, Edited by John G. Voeller

2.2 BASIC MECHANISM OF ELECTRIC POWER TRANSMISSION IN A LARGE GRID

Electric power transmission is predominantly realized by the system of alternating currents (AC system), in particular by three-phase currents. The alternating mode allows transformation of voltages by the relatively simple transformer. A single-phase system generates a stream of pulsating power. However, if three single-phase systems—as a three-phase system consists of three single phase systems—are combined in such a way that the three single phase systems are shifted one third time period each the shifted pulsating powers result in one constant power stream. Alternating voltages and currents create synchronizing forces between generators such that all machines rotate at the same speed yielding one unique frequency in the system.

The sum of the input powers, thus the generated output, is balanced by the total of the consumed load. The level is adjusted such that the speed that is directly proportional to the frequency of the voltage stays at the nominal level, in terms of frequency 60 or 50 Hz. Any disturbance in the power balance causes a change in frequency. Thus, a drop in frequency is a signal that there is not enough primary power or an excess of load. The Union for the Co-ordination of Transmission of Electricity (UCTE) has established rules [1] for the contribution of generators in subsystems (areas) to the correction or maintenance of frequency. Should there be a major drop in frequency, each subsystem has to be adjusted such that it contributes in terms of the so-called primary control an amount of power proportional to its annual consumption. The amount is derived from an assumed maximum loss of generation of 3000 MW, which does not cause more than 180 mHz of frequency deviation. Besides global changes in frequency, there are local changes on transmission circuits, which may cause overloads.

Another important phenomenon is the change in system voltage. The transport of large amounts of power over long distances leads to a decrease in voltage, which may cause instabilities. Generally, the whole system is an oscillatory system that breaks up if the amplitudes of the swings exceed a limit, and then there is a loss of generation, which could cause a chain reaction, that is, further losses. In order to counteract undesired oscillations, damping measures are installed in generators, explicitly in voltage regulators. The magnetic field in the generators is mainly responsible for the voltage, and the excitation system controlled by the voltage regulator reacts to any change in the voltage.

2.3 POWER FLOWS IN INTERCONNECTED GRIDS

Power flows in the grid are determined by the injected nodal powers, that is generation and consumption, and by the laws of the network acting on meshes and nodes, which consist of balances of voltages generated by currents times impedances in a loop or by balances of nodal currents. Impedances are characteristics of transmission lines. Because of mechanical properties, transmission lines can carry flows up to a predetermined thermal limit (conductor temperature determining the sag of conductors). Since the flows from one location to a distant one is fixed by the injected powers, the loss of a transmission circuit causes a redistribution of local flows. In extreme condition, the loss of one of the several parallel circuits causes a shift of the flow to the remaining ones, which can lead to overloads. A numerical example of a flow situation is given in Figure 2.1.

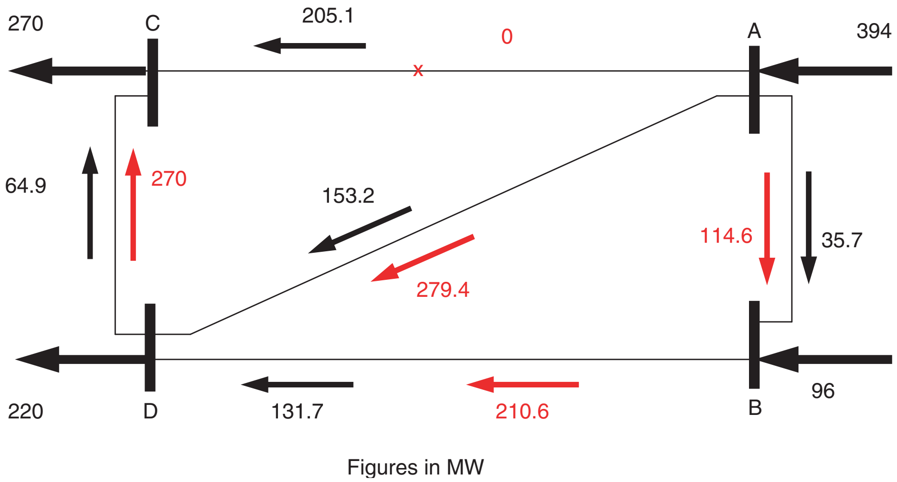

FIGURE 2.1 Effect of outage of one circuit (A–C): black figures flow in nondisturbed network and grey figures flow when circuit A–C is tripped.

The total of flows is given by the injections at nodes A and B equaling the output at nodes C and D, that is 490 MW. In the normal operation, the flows in the circuits A–C, A–D, and B–D are also 490 MW. When the line A–C is lost, the loading on A–D reaches 279.4 MW and on B–D 210.6 MW without any change in the total of input/output at the nodes.

2.4 THE EUROPEAN INTERCONNECTED SYSTEM—THE UCTE SYSTEM

The European interconnected system consists of three major parts that are connected by high voltage direct current (HVDC), namely, the central UCTE system, the Scandinavian network, and the network on the British Islands. Here, the interconnected synchronous AC system, the UCTE system, is of interest. It extends from Denmark to Spain and from France to Greece and the East European countries. It consists of 380- and 220-kV-transmission lines operated to a maximum of 420 and 245 kV, respectively. The structure of the grid is characterized by substations where a large number of transmission lines terminate and a larger number of substations where just three or four lines are connected. Typical line lengths for 380 kV are in the range of 100–150 km, sometimes 200 km. For 220 kV, they are considerably shorter (50 km). In France, the line lengths are above 200 km for 380 kV. In Germany, Switzerland, and Northern Italy, the grid is highly interconnected. Tie-lines (circuits crossing borders) are not numerous, except in Germany and Switzerland. The number of tie-lines to East European countries is relatively less.

Originally, the UCTE system had the function to provide the security of supply in continental Europe. For this purpose, the system has been developed over the last 50 years with a view of assuring mutual assistance between national subsystems. However, there has been a fundamental change of paradigms over the past one or two decades. The transmission infrastructure is no longer just a tool for mutual assistance, but has become a platform for shifting ever growing power volumes all across the continent. On the other hand, the development of the system is more and more affected by stricter constraints and limitations in terms of licensing procedures and construction times.

In the UCTE system, the annual production in the year 2006 amounted to 2584.6 TWh, the maximum load 390.6 GW (third Wednesday in December) and the annual load reached 2530.1 TWh. Electricity is produced in nuclear stations (37%), conventional thermal stations (47%), and in hydro stations (16%, figures of 1999).

Within a country, one or more control areas operated by independent transmission system operators (TSOs) and a large number of market participants (traders) are in existence. Today there are 29 TSOs in 24 countries. Energy is exchanged for various reasons, hydro to thermal, day to night and vice versa, as well as for economic benefits. The annual exchange 2006 among UCTE countries reached 296,822 GWh, that is 11.7% of the consumption. This is an increase over the time before the opening of the market as the exchanged energy is typically in the order of 9–10%.

2.5 MANAGEMENT OF THE SYSTEM

2.5.1 Before Opening of the Market

The vertically organized utilities were focused on their system and consumers. Tariffs for the exchange between voltage levels were fixed and state controlled. On the transmission level, an exchange of energy and power took place for the benefit of reducing reserves, peaking power, system regulation, better control of frequency, area control, and coordinated scheduling. The TSOs were the traders and the actors. The operation was coordinated by the rules of UCTE, which comprised the reserve management, primary, secondary, and tertiary frequency control, as well as security management.

2.5.2 In the Open Market

The Directives of the European Community introduced the liberalization of the electricity market [2], which was implemented step by step and is now nearly complete. The aim is a fully liberalized electricity market for all consumers whereby generation, transmission, and distribution are unbundled. The market participants are the traders and the TSOs are responsible for the technical aspects of operation. Explicitly, traders are utilities, power producers, and consumers, whereas TSOs are organizations for system control. In the open market, the exchange is governed by short-term economic objectives and trading takes place in a bilateral way and on central exchanges. However, there are also long-term contracts among partners being apart for short and long distances. As compared to the modes of operation, before liberalization flow patterns change markedly from hour to hour. There are countries that mainly export and import, that is France, Switzerland, and Germany export and Italy and Netherlands import. Some are net importers/exporters, others show changing patterns, and still other traders sell energy not originating in the own area.

As mentioned, TSOs are responsible for congestion management and system security; however, quite often they are not in command of controlling flows in their own area since the cause and origin of the problem lie outside the area, that is corresponding generation and consumption. The UCTE rules as laid down in the handbook [1] supplemented by the multilateral agreement (MLA [3]) are still in effect, the latter in particular focused on maintaining security. Congestion management is predominantly implemented in terms of auctions on cross-border transmission circuits. The methodology is market conform, but has limited effects as the TSOs lack information from neighboring areas and congestions within the areas are not handled. This is not satisfactory, as the annual exchange is increasing particularly in local zones such as in countries like Switzerland, France, Germany, Netherlands, and Italy.

2.6 THE ITALIAN BLACKOUT 2003

2.6.1 Introduction

The Italian transmission system is in a particular situation as the connection to the European network is geographically concentrated on the North only. The cross-border lines consist of not too many 380 kV circuits concentrated toward France and Switzerland. There is a 380 kV connection to Slovenia, but the network behind, that is, through Austria, consists of 220 kV lines only. The 380 kV loop through Hungary is not very effective because of high impedances, see Figure 2.2.

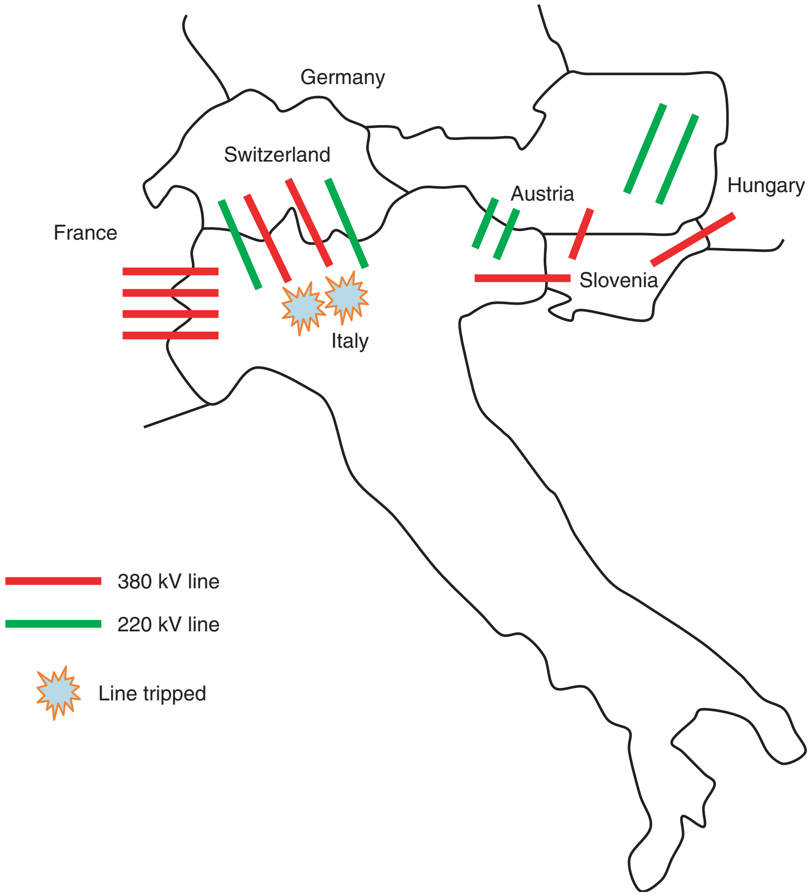

FIGURE 2.2 Italy—tie-lines to the north.

Because Italy does not generate nuclear energy and is with high energy costs due to fossil fired units, energy is imported from France, Germany, and Switzerland (for economic reasons) and the energy is stored in pump storage units during nights and weekends. The power flows predominantly over the circuits from France and Switzerland. As the flows are substantial and when it has been realized that the loadings of the tie-lines are critical, the countries involved established reference flows for the summer and the winter period, which were derived from power injections in the zone north of the Alps. According to these reference flows, the maximum import to Italy may reach 6500 MW in winter and 5500 MW in summer. These imports when appropriately distributed over the cross-border zones and circuits have been designed to guarantee an $(n-1)$-secure system. (The concept of $(n-1)$-security is discussed below.)

2.6.2 Factual Sequence of Events—Blackout September 28, 2003

On September 28, 2003, a Sunday, at 03:00 a.m., a typical situation existed where 6651 MW was imported and apparently used for pumping (pump load 3638 MW). At this time, the total consumption in Italy was 27,702 MW. The tie-line flows and the scheduled flows are as follows [4, 5]:

	Physical flows (MW)	Scheduled flows (MW)
Switzerland–Italy	3610	3068
France–Italy	2212	2650
Slovenia–Italy	638	467
Austria–Italy	191	223

The physical flows are those actually measured and the scheduled flows are those set on the load—frequency controllers.

The cross-border circuits between Switzerland and Italy consisted, at that time, of two 380 kV circuits (single lines) and several 220 kV circuits. The 380 kV circuits run from Mettlen to Lavorgo (Lukmanier line) and Sils to Soazza (San Bernardino line), both cross the Alpes. The latter substations are still in Switzerland, but are connected via 380 kV lines to stations in Italy.

In the following paragraph, the exact sequence of events is discussed as reported in Refs. [4, 5].

At 03:01:42 a.m., the 380 kV circuit Mettlen–Lavorgo tripped due to a tree flashover. The automatic reclosure was unsuccessful because of a phase angle difference of 42° across the open breaker (the setting on the breaker was 30°). A subsequent manual trial was just as unsuccessful. As a consequence, the 380 kV circuit Sils–Soazza overloaded and reached 110% of its thermal rating. At this point, the state of $(n-1)$-security was lost. The operator at the control center in Laufenburg (at that time ETRANS, now Swissgrid) was unaware of the urgency of the situation. The Swiss operator noticed that the actual flows to Italy were roughly 300 MW above the scheduled value and requested a reduction of the imports from the Italian TSO (GRTN–Gestore della Rete di Trasmissione Nationale) by telephone at 03:11 a.m. The tolerable time for the reduction of the current was 15 min.

The reduction was performed and the imports reached the scheduled value after 10 min. However, the reduction was not sufficient and at 03:25:11 a.m., the circuit Sils–Soazza tripped due to a tree flashover (probably because of a high sag caused by the overload). Immediately afterwards further 220 kV circuits tripped, and at 03:25:28 a.m. the Italian network lost synchronism with the rest of the UCTE system. The Italian system has lost about 6500 MW, the frequency dropped causing the shutdown of generating stations, which led to the blackout (definite at 03:27:58 a.m. when the frequency dropped below 47.5 Hz). The rest of the UCTE system experienced a rise in frequency to 50.25 Hz with swings to 50.3 Hz. In the immediate vicinity of the Italian border in Switzerland (Ticino and Valais), the systems were lost (blackout). Otherwise the UCTE system was not affected, although it experienced the frequency changes.

The report [4] mentions four main reasons for the blackout:

1. Unsuccessful reclosing of the line Mettlen–Lavorgo (Lukmanier) because of a too high phase angle difference.
2. Lacking sense of urgency regarding the Sils–Soazza (San Bernardino) line overload, and call for inadequate countermeasures in Italy.
3. Angle instability and voltage collapse in Italy.
4. Right-of-way maintenance practices.

However, the principle of $(n-1)$-rule in chapter “Security and reliability standards—safety of the system” states that a single incident must not jeopardize the system, which implies that after a loss of the (n–1)-state the system is supposed to return to the $(n-1)$-state as soon as possible. This means identifying countermeasures which would enable the system to be brought back to a secure state. The report states that the appropriate countermeasure after the loss of the Mettlen–Lavorgo circuit would have been the shutting down of the pumps in the storage plants in Italy having a load of about 3500 MW.

2.6.3 Comments on and Interpretations of the Events/Findings

The reasons given in Ref. 4 are certainly true and correct, but do not give the complete picture. In particular, the first two points need further explanations. As far as point 1 is concerned it has to be realized that there was a substantial flow across the Swiss network where the circuit Mettlen–Lavorgo is imbedded. This flow caused the phase angle difference of 42°, which should have been below 30°. The Swiss Federal Office of Energy (SFOE) investigated the situation and came to the conclusion that the flow situation has been far away from the reference flow [6]. The reference flow would have produced a phase angle difference of 20° and there would have been no overload on the circuit in the first place. A simplified network illustrates the effect of flows on the phase angle difference at an open breaker, see Figure 2.3.

The phase angle difference is proportional to the sum of the flows C + D + E or to the flow A or B. A phasor diagram is shown on the right-hand side where phasors are the terminal voltages. The tree flashover is probably due to excessive sag of the conductors, which was caused by the overload. Hence, the flow situation is the primary cause of the tripping and the unsuccessful reclosing. The report states that the system was still $(n-1)$-secure at 03:00 a.m., which would have been correct if the countermeasures had

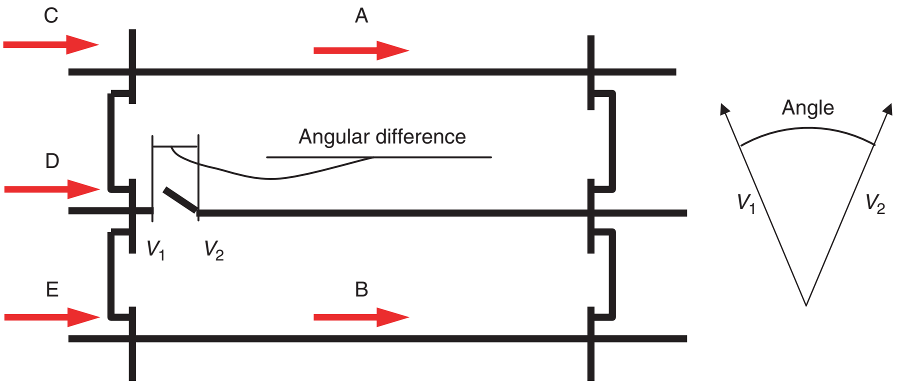

FIGURE 2.3 Flows generating phase angle difference at open breaker.

been identified and implemented. This is one of the basic flaws in the whole process that must be further criticized by the following.

A quite similar disturbance happened in the critical zone of the Swiss network in the year 2000, which is documented in the annual report 2000 of UCTE [7]. On September 8, 2000, the San Bernardino (Sils–Soazza) 380 kV circuit tripped at 9:46 p.m. and at 10:11 p.m. the Mettlen–Lavorgo (Lukmanier) 380 kV circuit tripped, followed by trippings of 220 kV circuits between Switzerland and Italy as well as between Austria and Italy. These line trips led to load displacements on France to Italy line resulting in a flow of 3900 MW on 380 kV and 220 kV lines. As a result of this overloading, these transfrontier lines together with five other 380 kV lines in France reached their 20 min overload protection threshold, others even their 10 min overload protection threshold.

Italy was required to produce an additional 1800 MW, in order to ensure operational security without network separation. It was not possible to implement a sufficiently rapid reduction of nearly 1500 MW in exchange programs between Italy and Switzerland. For these reasons, the UCTE network frequency rose to 50.15 Hz.

The report mentions numerous problems that took place in the following hours and on September 9, 2000. However, no disturbances in the distribution were recorded. What is important is the concluding statement in the report:

> As a result of the events described above, TSOs in Italy, France, Switzerland have agreed to a joint procedure for the improvement of communications and the implementation of arrangements for the modifications of exchange programs in case of emergency.

The events after 03:00 a.m. on September 28, 2003, do not indicate that such a joint procedure has been established. Further, it is an open question what the countermeasures would have been if the outages had taken place during the week around 11:00 a.m. when no pumps were in operation.

Unless one would resort to substantial load shedding in Italy (the remedial measure to point 3 above), the solution to the problem is careful congestion management whereby flow patterns close to the reference flow are maintained and the security is monitored whenever the load changes. Swissgrid, the Swiss TSO, has implemented a security monitoring scheme [8], which generates security information within half a minute whereby the Swiss network plus the surrounding network comprising 6000 nodes is modeled. Today this is the only realistic and practical procedure to master the problem.

2.7 THE SYSTEM DISTURBANCE NOVEMBER 4, 2006

2.7.1 Situation and Actions before the Disturbance

On November 4, 2006, at 10:10 p.m., the European network was split into three parts caused by a planned outage of a double circuit 380 kV line in northern Germany where the consequences were meant to have been orderly estimated and considered secure, but finally evolved to a cascading process. The process separated the UCTE and caused low-frequency load sheddings, but did not lead to a complete blackout. A precondition to the disturbance was the heavy cross-border flow situation between East and West Germany on the one hand and Eastern Europe and South Eastern Europe on the other hand. Since this is essential to the understanding of the disturbance of the network areas, the generation and cross-border flows are shown in Figure 2.4 [9].

The East–West flow of 9260 MW was caused by a heavy load in the Netherlands, which was supplied by wind generation in the northeast. The double circuit line that was switched was the Conneforde–Diele line shown in Figure 2.5 located in the far northwest corner of Germany.

The line belongs to the network of E.ON, the important German utility and the taking-out-of-service was planned for November 5 and prepared the days before. The operation was requested by a shipyard for passing of ship on a canal that is crossed

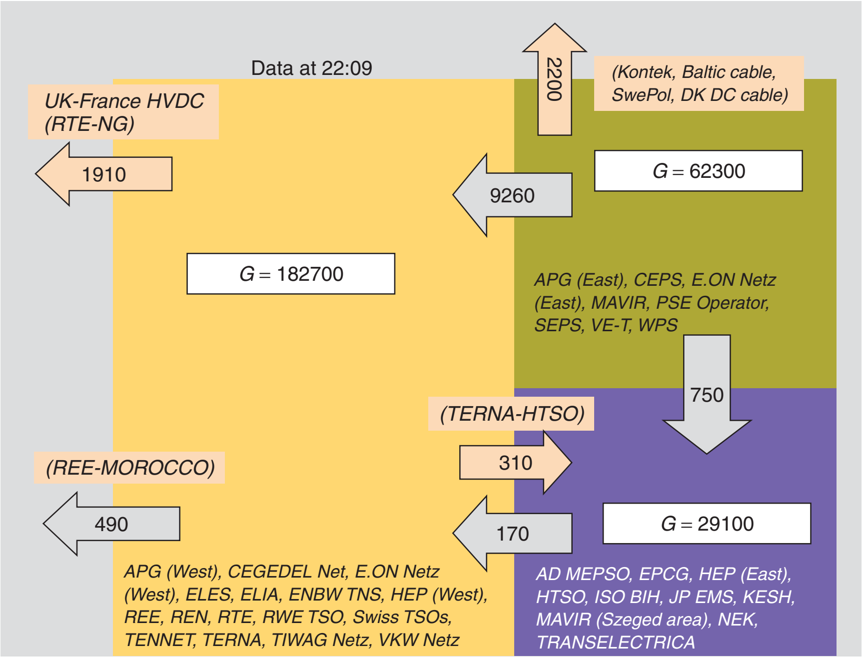

FIGURE 2.4 Schematic of UCTE system: three areas before separation at 9:09 p.m. and generation and cross-border flows.

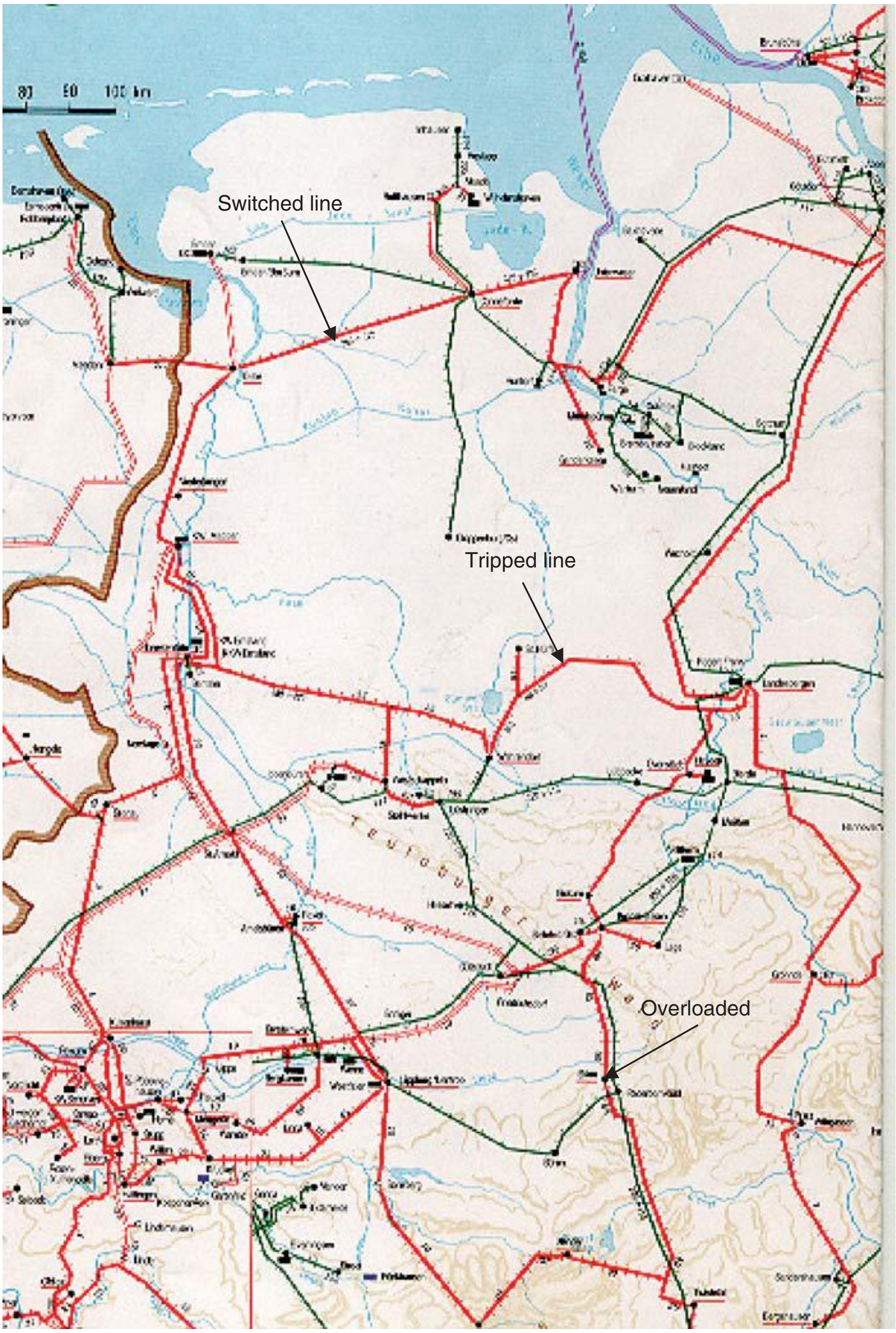

FIGURE 2.5 Line diagram, section of northern Germany.

by the line. It was also coordinated with Tenne T, the TSO of the Netherlands. E.ON Netz, the TSO of E.ON, carried out an analysis of the impact of the operation using standard planning data. As no violation of the $(n-1)$-criterion was detected, E.ON Netz provisionally approved the switching off. On November 3, around 12:00, the shipyard requested E.ON Netz to advance the disconnection of the line by 3 h, to November 4 at 10:00 p.m. A provisional agreement was given by E.ON Netz after a new analysis did not reveal a violation of the $(n-1)$-criterion. At this point, the TSO of Rheinisch-Westfaelisches-Elektrizitaetswerk (RWE) of the adjacent German network and the TSO of Tenne T were not informed about this procedure, so no special security analyses were made.

For the new situation, it was not possible to reduce the exchange program between Germany and the Netherlands including the outage of the Conneforde–Diele line (agreed timing, setting of capacities, and auctions). Further, there was no indication of the switching operation in the planning tools and data, such as day ahead congestion forecast (DACF), by E.ON Netz to all UCTE TSOs on November 3 with the forecast for November 4 at 10:00 p.m. and beyond.

As late as 6:00 p.m., E.ON Netz informed Tenne T and RWE TSO about the new time for the disconnection of the line.

At 9:29 p.m., a load flow calculation by E.ON Netz did not indicate any violation of limit values. On the basis of an empirical evaluation of the grid situation, E.ON staff assumed, without numerical computations, that, after the disconnection of the line, the security of the system would be met.

RWE TSO also made a load flow calculation and an $(n-1)$-analysis at 09:30 p.m. just before the opening of the line, which confirmed that the RWE grid would be highly loaded but secure.

2.7.2 Evolvement of the Disturbance

The two circuits of the Conneforde–Diele line were switched off at 9:38 p.m. and 9:39 p.m. Shortly afterwards, E.ON Netz received warning messages about the high loading on a line south of the area shown in Figure 2.5 and at 9:41 p.m. RWE TSO informed E.ON Netz about the safety limit of 1795 A on the line Landesbergen–Wehrendorf, an interconnection between the E.ON network and the RWE network. This line is shown in Figure 2.5. However, at this point in time the critical current on this line has not been reached. The report [9] documents that the protection settings on either sides of this line were different and the TSO of E.ON was not aware of this fact, that is tripping current 3000 A on the E.ON side and 2100 A on the RWE side. In phone calls between the TSOs of E.ON, RWE, and Vattenfall, up to 10.00 p.m. the situation was considered to be critical and apparently RWE TSO informed E.ON Netz about the settings.

Between 10.05 p.m. and 10.07 p.m., the load on the 380 kV line Landesbergen–Wehrendorf increased and exceeded the warning value of 1795 A, which caused the RWE TSO to request from E.ON Netz an urgent intervention to restore the security of the system. E.ON Netz made an empirical assessment of corrective switching measures in terms of coupling of the busbars in Landesbergen expecting a reduction of the line current by about 80 A. The operation was done at 10:10 p.m., but resulted in the opposite effect. The line current increased and caused the tripping of the Landesbergen–Wehrendorf line, leading to a subsequent cascading opening of circuits along the vertical line shown in Figure 2.4 and separation of the southeastern network.

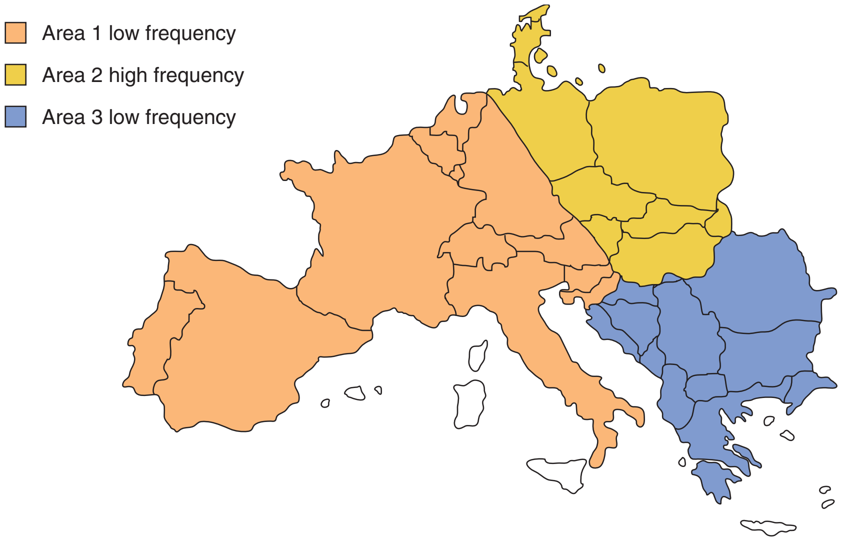

FIGURE 2.6 Separation of the UCTE network into three parts.

2.7.3 Consequences of the Opening

The European network was separated into three parts, as shown in Figure 2.6, whereby different frequency patterns developed. Since a substantial flow between the East and West part was interrupted, the area 1 experienced a drop and the area 2 a rise in frequency. In area 3, there was a frequency drop but it was only 200 mHz. The low frequency in areas 1 and 3 caused a series of load sheddings spread over the areas and the loss of loads was substantial, that is between 3% and 19% of the load. In some areas, pumps were disconnected between 240 and 450 MW. In all areas, generation was tripped, namely, 10,909 MW in total. The switching operations caused heavy intersystem flows after 10:10 p.m. A complete blackout did not result in neither of the areas. This allowed the restoration and the resynchronization of the areas fairly soon after the initial disturbance.

The actions of the resynchronization process showed three different phases, namely:

- resynchronization trials that did not result in real interconnection;
- resynchronization attempts that resulted in real interconnection, but failed after a few seconds;
- successful resynchronization steps.

The milestones of resynchronization were first successful reconnection of tie-lines between areas 1 and 2 at 10:47 p.m. when areas 1 and 2 were connected, and area 3 was connected at 10:49 p.m.

The problems in the resynchronization process were the missing information on the state of generating units and of the network, as well as noncoordinated trials of operators to synchronize generators. In particular, actions in the distribution network were completely non-coordinated.

2.7.4 Failures and Mistakes that Led to this Disturbance

On the basis of report [9], several items that caused the disturbance can be identified. The main cause is the omission of contingency analyses at various stages of the preparation of the switching operation, both by E.ON Netz and RWE TSO. This applies to the points in time before the opening of the line, right after the opening of the line, and before the coupling of the busbars in Landesbergen. It is not just an analysis of the respective own area, which should have been performed, but a comprehensive analysis of the own area including the surrounding network, that is E.ON network plus RWE network plus Tenne T network as it is possible today and described in [8]. Another item is the missing information of RWE TSO and Tenne T by E.ON Netz about the advance of the switching of the line. This did not allow the TSOs to check the consequences of the switching early enough.

A crucial item was the different protection settings on the Landesbergen–Wehrendorf line about which E.ON Netz was not aware. It was not only this line which was heavily loaded, but also several lines in the E.ON and RWE network, which when tripped, could have caused the disturbance. The load increase between 10:00 and 10:10 p.m., which led to the tripping, was also affected by the change in exchange programs that usually takes place around this time, for example, 340 MW from Germany to the Netherlands.

Generally, there was insufficient coordination between the TSOs. According to [9], this was considered the second main cause of the disturbance.

2.8 UNBUNDLING AND DECENTRALIZATION—FEATURES IN CONTRADICTION TO SECURITY

Further to the detailed discussions and conclusions from the reports on disturbances, there are general features of the liberalized system in Europe, which are detrimental for the security of the network. One of the features is the requirement of the Directive of the European Community to unbundle generation, transmission, and distribution. Unbundling is justified in the normal state of the system. However, in a critical situation, the cooperation of generation and transmission is absolutely necessary and therefore unbundling has to be suspended. A TSO must have direct access to generation for the correction of a flow. Above all, the European system is decentralized. According to [9], there are 29 TSOs in 24 countries which manage an area or subsystem. But for the purpose of security, a comprehensive control over a wide region, that is overlapping the own, would be necessary. Each TSO is obliged to carry out such an analysis and TSOs have to cooperate and communicate in critical situations.

Thus, decentralization, congestion management, and security control in the European system are unresolved items.

2.9 CONCLUSIONS

The large-scale electricity transmission grid with a decentralized control structure, that is independent transmission operators as in the UCTE system, and under the concept of unbundling is only partly suited to manage disturbances and to avoid blackouts, at least with the presently implemented tools. Unbundling and decentralization are detrimental for security as the electricity grid acts as a whole, in terms of frequency, voltage, and flows, from one end to the other. Contracts over long distances and the ensuing flows are difficult to control by TSOs. Hence, cooperation and closer communication is needed.

REFERENCES

1. UCTE. *Operation Handbook*, www.ucte.org.
2. Directive European Union 2003/54/EG (previous 96/92/EG).
3. Multi-Lateral Agreement (MLA) in UCTE. *Operation Handbook*, http://www.ucte.org/e default asp.
4. UCTE (2003). *Report–Interim Report of the Investigation Committee on the 28 September 2003 Blackout in Italy*, 27 October, www.ucte.org.
5. Gheorghe, A. V., Masera, M., Weijnen, M., and De Vries, L. (2006). *Critical Infrastructures at Risk—Securing the European Electric Power System*, Appendix A.1 Learning from the Past—Electric Power Blackouts and Near Misses Europe. Springer, New York.
6. SFOE Swiss Federal Office of Energy (2003). *Bericht über den Stromausfall in Italien am 28. September 2003*, November (Report on the blackout in Italy). SFOE Swiss Federal Office of Energy, Switzerland.
7. UCTE 2000 Annual Report, www.ucte.org.
8. Nordanlycke, I., Bossert, G., and Glavitsch, H. (2007). Security and congestion management tool for the use in extended transmission systems. *IEEE Powertech 2007*. Lausanne, July 1–5, www.ucte.org.
9. UCTE (2006). *Final Report - System Disturbance on 4 November 2006, www.ucte.org*.

FURTHER READING

Taylor, C. W. (1994). Power System Voltage Stability McGraw-Hill International Editions—Electrical Engineering Series.

Philipson, L., and Lee Willis, H. (1999). *Understanding Electric Utilities and De-Regulation*, Marcel Dekker, Inc., New York.

Shahidehpour, M., and Alomoush, M. (2001). *Restructured Electrical Power Systems—Operation, Trading, and Volatility*, Marcel Dekker, Inc., New York.

Kundur, P. (1993). *Power System Stability and Control*, McGraw-Hill Inc., New York.

3

INTERDEPENDENT ENERGY INFRASTRUCTURE SIMULATION SYSTEM

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3.1 INTRODUCTION

IEISS was derived from the energy interdependence simulation (EISim) and simulation object framework for infrastructure analysis (SOFIA) software architectures that have been applied routinely at Los Alamos since the mid-1990s. The National Infrastructure Simulation and Analysis Center (NISAC), supported by the Department of Homeland Security, Office of Infrastructure Protection, funds for the use of this software. The NISAC program was established to meet the need for a comprehensive capability to assess the national system of interdependent infrastructures. In the USA PATRIOT Act of October 2001, NISAC was chartered to “serve as a source of national competence to address critical infrastructure protection and continuity through support for activities related to counter terrorism, threat assessment, and risk mitigation”.

This chapter discusses the underlying simulation concepts, application of interdependent energy infrastructure simulation system (IEISS) to an interdependency case study of urban infrastructure, and IEISS applications to other problems of national interest.

Interconnected and interdependent energy infrastructures are extremely complex systems, consisting of physical facilities (such as power plants and refineries), transmission lines, phone lines, roads, railways, waterways, and so on, as well as human decision makers (e.g. consumers, legislators, investors, and chief executive officers). Examples of critical infrastructures that are interconnected and interdependent are shown in Figure 3.1.

A comprehensive simulation tool is needed to model the nation’s key infrastructures (e.g. energy, communication, and transportation) and their intra/interdependencies. However, these dependencies must be identified and understood before infrastructure protection, mitigation, response, and recovery options can be provided. Although existing technology well analyzes single-domain infrastructures, severe limitations arise when this technology is applied to interdependent infrastructures. For these cases in which multiple infrastructures are considered, analysts typically treat these interdependencies in an

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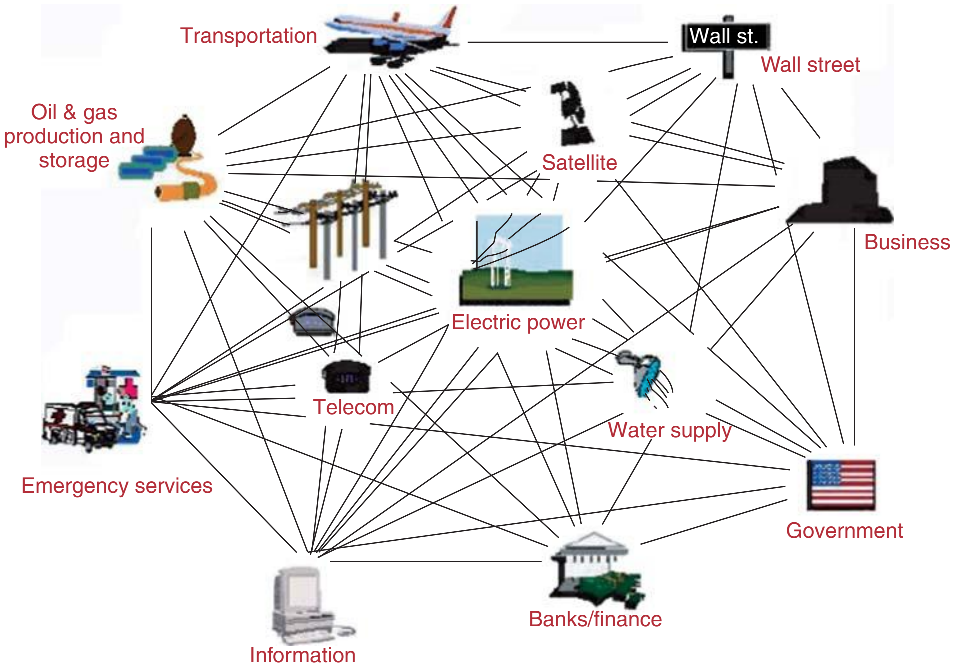

FIGURE 3.1 National interconnected and interdependent infrastructures.

ad hoc manner. To represent the complex, nonlinear, and interdependent nature of these infrastructures, advanced computer simulations are needed. Without these simulations, it is simply too expensive, too risky, and too time consuming to determine the impact of policy and security decisions.

3.2 IEISS SIMULATION CONCEPTS

An infrastructure interdependency is defined as a physical, logical, or functional connection from one infrastructure to another, where the loss or severing would affect the operation of the dependent infrastructure. Although short-term service interruptions of energy infrastructures routinely occur, catastrophic system failures, or large-scale blackouts, are rare events. As infrastructures become more complex and interdependent, the probability of having large-scale outages increases. Because a component failure in one infrastructure does not necessarily result in a propagating failure in another interdependent infrastructure (or for that matter, within the same infrastructure), this cascading phenomenon is difficult to analyze. An example of interdependencies among network-like infrastructures is given in Figure 3.2. “Network-like” refers to an inherent topological feature of the infrastructure itself, namely, a connected structure of linked nodes.

The horizontal layers in the figure represent dependencies within an infrastructure, and the vertical lines indicate interdependencies between infrastructures. Although Figure 3.2 shows only physical infrastructures, future capability will include nonphysical infrastructures as well, such as financial and/or other economic networks. IEISS does not replace single-infrastructure tools since existing technology analyzes these domains in sufficient

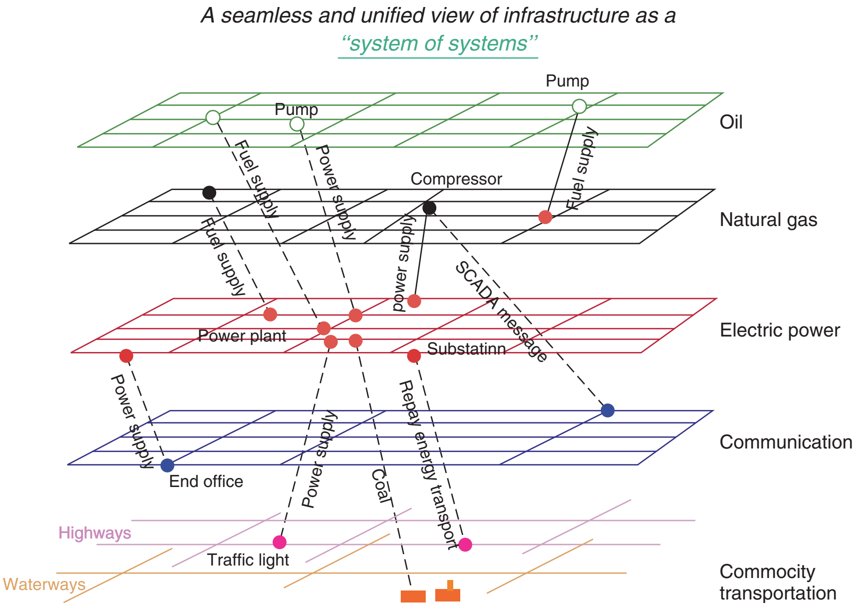

FIGURE 3.2 Illustration of interdependencies among network-like infrastructures.

detail. However, when this technology is applied to interdependent infrastructures, severe limitations usually exist.

IEISS relies on an actor-based (or object-oriented) modeling approach of infrastructures [1]. Each physical, logical, or functional entity in an infrastructure corresponds to a software *actor* (sometimes called a *software agent*) that has a variety of attributes and behaviors that mimic its real-world counterpart. The connections within or between infrastructures are represented by connections between the relevant actors, and the actors interact in the software through a message-passing protocol. Mathematically, infrastructures can be represented by graphs. Thus, any infrastructure(s) that can be represented in terms of a dependency graph can be modeled using this actor-based, message-passing representation. This approach is suitable for a wide variety of network-like infrastructures.

3.3 THE COMPLEXITY OF MULTIPLE INFRASTRUCTURES

A simulation of coupled infrastructures necessarily requires the use of multiple, heterogeneous algorithms [2]. Each infrastructure under consideration has its own dynamic laws and, thus, its own types of algorithms. It may be useful to mix different solution methods in the same simulation because of their varying accuracy and speed or to compare the results of simulations using different algorithms. Ideally, "pluggable" algorithms could be attached individually to each actor in the system or to groups of actors. Mixtures of algorithms may be required by geography, infrastructure, or time.

Because of the potential complexity of coupled infrastructures, it is important that the solution algorithms be able to handle problems involving the "forward" simulation of systems and the "inverse" search problems. That is, given an initial state of the system, its evolution could be followed forward in time or, given the final state (typically involving loss of service), initial states could be determined that might evolve to this final state if a given number of contingencies were to occur.

When one or more interconnected components are forced out of service because of an operational or intentional failure, affected dependent or secondary components are also treated by IEISS as interdependency. This approach is based on the service area/outage area concept [3, 4]. For example, if an electric power substation is forced out of service, a polygonal representation of the service area normally served by the component is calculated. If components from other infrastructures lie within the calculated service area boundary and these components are dependent on the services of the failed substation, a propagation of the failure to dependent infrastructures is assumed. If the service areas of any affected infrastructures cannot be mitigated or reduced in extent through recovery measures, they are assumed to represent the outage area. This concept is further discussed in the next section.

Finally, if a service area can be estimated for all affected infrastructures, the simulation approach for interdependent cascading failures can be illustrated by the logic flow diagram shown in Figure 3.3. The simulation is initiated by creating a "contingency" event that involves single (or multiple) outages in one or more infrastructures. Steady-state solutions are then obtained for all infrastructures with key attributes reported (e.g. pressure or flow). If an attribute is not within its normal operating range, for example, a pipeline is operating above its maximum allowable operating pressure, the associated components are subject to limit violations [5]. Limit violations must be mitigated or else severe consequences can result. Mitigation can be accomplished by a variety of measures such as dispatching or

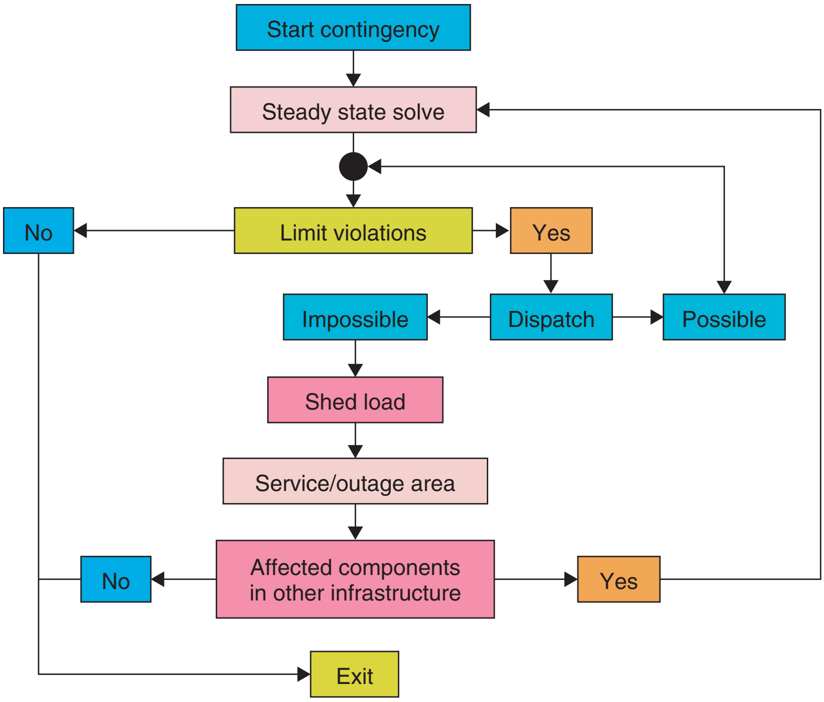

FIGURE 3.3 IEISS logic diagram describing network limit violations.

reducing demand. Dispatching requires adjustments to operating parameters of variable equipment such as generators or compressors. The dispatch box shown in Figure 3.3 contains algorithms to eliminate limit violations.

If the contingency can be mitigated by dispatching, limit violations are rechecked and the simulation is ended (“possible”). However, if further violations exist (“impossible”), IEISS sheds customer load near the contingency and then calculates outage areas. Affected components in other infrastructures are also identified. Another simulation will be required to determine if loss of the affected components cause violations within their respective infrastructure(s) or propagation of effects is stopped. The IEISS simulation process ends when all limit violations have been eliminated. The final result is a list of outage areas, failed components, history of cascading events, and so on.

3.4 IEISS CASE STUDY: URBAN INTERDEPENDENCIES

A key element in modeling interdependent infrastructures is the ability to predict the propagation of a perturbation. This condition results from a component failure created within an infrastructure, which cascades to other interdependent infrastructures. This cascading effect is a key issue, but usually the least understood phenomenon. Although short-term service interruptions of energy infrastructures are routine in many areas, catastrophic system failures, or large-scale blackouts, are rare events. As urban infrastructures become more complex and interdependent, the probability of having large-scale outages increases.

The underlying concepts of interdependency and application of IEISS are illustrated by a fictitious example. Interconnected electric power and natural gas component attributes were input into the IEISS model, which are notionally representative of urban networks in most US cities. The model incorporated multiple layers of components operating at different voltages and pressures. Because of the network-like features, disruptions to key components in one layer can affect the operation of colocated components in other layers, creating an interdependency event. During the analysis, IEISS reported greater effects than would have resulted if single components were individually outaged.

The first phase of this event requires simultaneous loss of two components: an electric substation and a natural gas pipeline junction. An outage of the natural gas pipeline junction disrupts natural gas delivery to gas-fired power plants located approximately 10 miles to the south. The simultaneous outage of a 230-kV electric substation completes the initiating event. Components “A” and “B” are located approximately 30 miles apart as shown in Figure 3.4.

Following the initial loss of components, high-voltage electric transmission lines will be overloaded. This condition forces the utility to shed customer load to avoid equipment damage and to stabilize the local network. In turn, this action will create an outage area, as shown in Figure 3.5.

The outaged electric substation provides connections to areas west of this location. Under normal operating conditions, electric generators are capable of providing more power than needed locally, so excess is exported to the east. Following a loss of electric generation due to pipeline junction “A” outage, customer demand must be met by supplying from the east. Three 230-kV transmission lines normally support this power flow. However, two of three lines originate at the outaged electric substation “B”. Since this

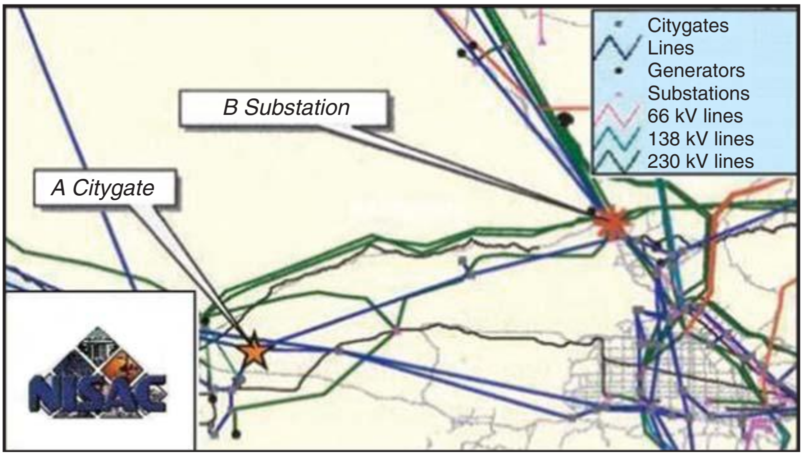

FIGURE 3.4 Natural gas (NG) and electric power (EP) components in the IEISS model, highlighting locations of outaged nodes.

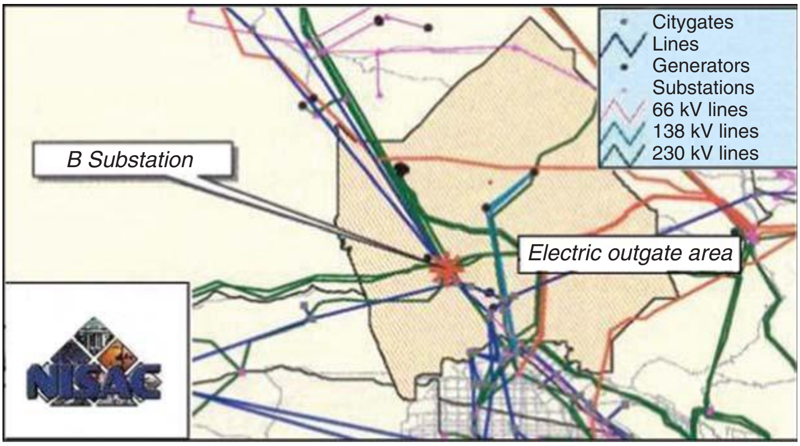

FIGURE 3.5 Outage area (gray shade) resulting from the loss of substation "B".

component is outaged, power can only be supplied by a single 230-kV line, which is severely overloaded. The result is an additional area of customer load shed, as shown in Figure 3.6.

Because large area is affected by this event, many businesses and facilities critical to continued operation of urban infrastructure would lose electricity and natural gas service. The total outage area encloses nearly 2700 sq. miles. On the basis of average business sales density, the direct cost of a 3-day interdependency outage would total approximately $150 million. Indirect costs due to supply chain disruptions, noninsured loss of perishable goods, and related items may also be significant. In addition, key emergency facilities such as hospitals, telecommunication end offices, police, and fire stations would be outaged forcing extended reliance on emergency backup power.

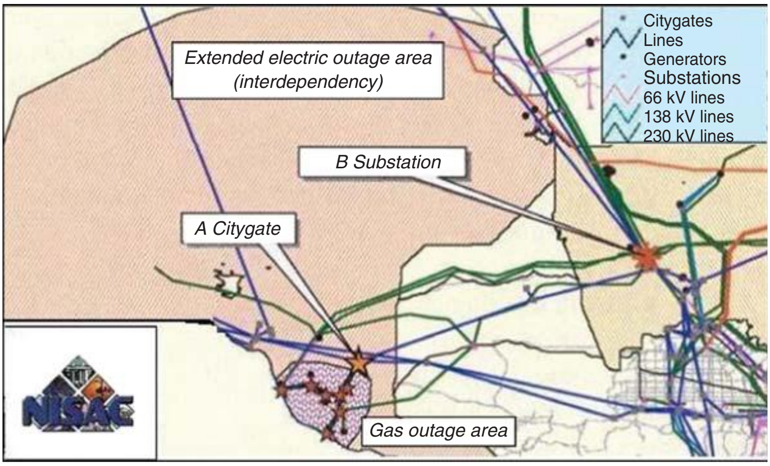

FIGURE 3.6 Additional load shed due to transmission line overload from electric substation "B" results in the final interdependency event.

REFERENCES

1. Bush, B. W., Bush, A. B., Fisher, R., Folga, S., Giguere, P., Holland, J., Hurford, J., Kavicky, J., Linger, S., McCown, A., McLamore, M., Pontante, E., Rothrock, L., Salazar, M., Shamsuddin, S., Unal, C., Visarraga, D., and Werley, K. (2005). *Interdependent Energy Infrastructure Simulation System–IEISS Version 2.1 Technical Reference Manual*, Report LANL-D4-05-0027, Los Alamos National Laboratory.
2. Unal, C., Werley, K. A., and Gigue, P. (2001). *Energy Interdependence Modeling and Simulation*, Report LA-UR-01-1879, Los Alamos National Laboratory.
3. Linger, S. P., Toole, G. L., and McPherson, T. (2001). *A Primer on Estimating Electrical Service and Outage Areas Using GIS and Cellular Automata Based Methods*, Report LA-UR-01-0490, Los Alamos National Laboratory.
4. Werley, K. A. (2002). *Constrained Cellular Colonization (C3) for Estimating Service and Outage Areas in Electric Power Transmission Networks (Rev. 4)*, Report LA-UR-01-4845, Los Alamos National Laboratory.
5. Werley, K. A. (2001). *An AC Dispatcher for Relieving Problems within Electric Power Transmission Networks*, Report LA-UR-03-8266, Los Alamos National Laboratory, pp. 1–16.

FURTHER READING

National Infrastructure Protection Plan (2006). http://www.dhs.gov/xprevprot/programs/editorial_0827.shtm.

4

OBJECT-ORIENTED APPROACHES FOR INTEGRATED ANALYSIS OF INTERDEPENDENT ENERGY NETWORKS

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4.1 INTRODUCTION

In many fields, there is a growing interest for tools to study the interdependencies of different areas of activity or production. Driven forces in this process have been security, economy, and environmental problems, where the cross effects of policies are highly linked [1]. In the literature, an important part of the investigation is dedicated to the study of critical infrastructure in order to prevent possible catastrophes [2], whereas another line of research is given by environmentally sustainable development [3, 4]. The underlying objective of those works is to study the cross effects of policies in different fields in order to measure their effect on environmental conditions [5]. All these studies recognize the high complexity of the problem, which is characterized by multiple agents and decision makers, large-scale systems with numerous components, nonlinear coupled subsystems, spatially distributed, adaptive in time, and investment decisions of discrete nature. Another aspect of complexity is the need of know-how integration of different disciplines. The mathematical formulation of these problems usually leads to extremely complex systems. In addition, the trend of market liberalization toward decentralized decision process has increased even further the complexity of the problem [6, 7].

This chapter is organized in seven sections. Section 2 presents the general models used to represent the transportation and energy networks. Section 3 presents the classes and objects relationship. Section 4 describes the software developed according to the system models. In Section 5, the methodology to state the scenarios for the studies is presented. In Section 6, a case study considering the network in the Chilean territory is developed. Finally, in Section 7, the main conclusions of this section are summarized.

Energy Systems Security, Edited by John G. Voeller

4.2 SCIENTIFIC OVERVIEW

In the literature, an important part of the investigation is dedicated to the study of critical infrastructure in order to prevent possible catastrophes [8]. This topic was particularly sensitive during 1999 due to the Y2k effect. Another line of research is given by environmentally sustainable development, where the cross effects of policies in different fields on the improvement of environmental conditions are studied [9]. It is recognized that the high complexity of the problem is characterized by

- large-scale systems with numerous components;
- hierarchical multiple noncommensurable, conflicting, and competing objectives;
- multiple agents and decision makers;
- multiple governmental agencies with different missions, resources, timetables, and agendas;
- multiple constituencies;
- multiple transcending aspects and functions;
- nonlinear coupled subsystems;
- spatially distributed, adaptive in time; and
- investment decisions of discrete nature.

Overall, analysis and design of complex, large-scale nonlinear dynamic interacting systems constitute an open theoretical challenge.

The object-oriented programming (OOP) offers a methodological alternative to deal with the problem of interactions among energy and transportation. Specifically, in this chapter the development of activity models for each sector and a method for studying their effects on the environment is proposed. This methodology should be capable of measuring the impact due to the future implementation of technological improvements and policies at a country-wide level.

4.3 SYSTEM MODELING

The modeling approach presented in this section is inspired by previous research work [6, 7, 10] based on two main criteria. The first criterion imposes that the main feature of the modeling technique is versatility, that is, it must be capable of being used for the electricity, fuel, and transportation sectors. In addition, a systematic approach to deal with the problem of interdependencies among those sectors is required. To achieve these tasks, the modeling must fulfill the following needs:

- consistent system and component modeling (scaling, databases, and granularity);
- well-defined system frontiers;
- adequate modeling of the interdependencies among different sectors;
- activity models and tools (i.e. agent-based and game theory) inside each sector;
- data mining and visualization.

In the field of software development, two advancements have gained wide spread importance and acceptance: the OOP [11, 12] and the graphical user interface (GUI) [13]. The OOP has recognized advantages that concern flexibility, expandability, maintainability, and data integrity. In this field, the unified/universal modeling language (UML) is a standardized visual specification language for object modeling. UML is a general-purpose modeling language that includes a graphical notation used to create an abstract model of a system, referred to as a *UML model* [10, 12]. This approach is the conceptual base for several popular OOP languages.

Likewise, the GUI improves the user interaction with the computer allowing a more comprehensive analysis tools manipulation and data interpretation. Accordingly, this work applies an OOP methodology to the new energy market structure in order to create a simulation software package.

The second criterion states that, from a physical point of view, the interdependencies among large-scale infrastructures, such as electric power, transportation, and fuel sectors, often have a network structure (Fig. 4.1).

This structure reflects an explicit, physical set of network interconnected devices. Also, it can handle implicit interconnections created by communications, control, and functional dependence. Thus, according to the above criteria a model based on the object-oriented (OO) paradigm was chosen in this work. The large box in the center of Figure 4.2 represents the physical models (urban and interurban) where each network physically and functionally interacts. The regulatory, economic, and technological frameworks are also highlighted as relevant inputs to the two major models. The outputs of the modeling framework are the transport activity levels that are used to compute the fuel and energy consumptions and the environmental impact of the emissions resulting from future economic and technological developments.

The individual characteristics of power, fuel, and transportation components are described by object attributes. On the other hand, the information exchange among objects is represented by messages following the OOP paradigm.

The object modeling technique has been used for developing the object models for each network.

They are shown in Figure 4.3.

In the OOP terminology, generalization of a data object along with its data variables and methods is a class of data objects. The data variables are referred to as *class attributes* and an instance of a class is called an *object*. The concept of inheritance makes it possible to define subclasses of a class, which share characteristics of the parent class and so on.

The proposed modeling breaks down a “system component” object into three subclasses: namely, “fuel component”, “power component”, and “transportation component”. Each of these components makes a further use of inheritance to encompass all the

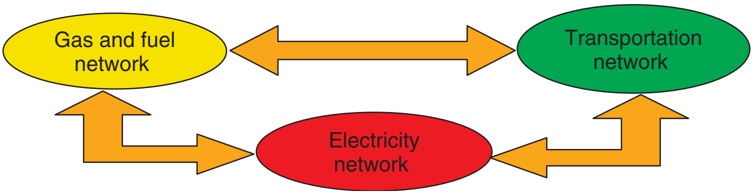

FIGURE 4.1 Interdependencies among large-scale infrastructures.

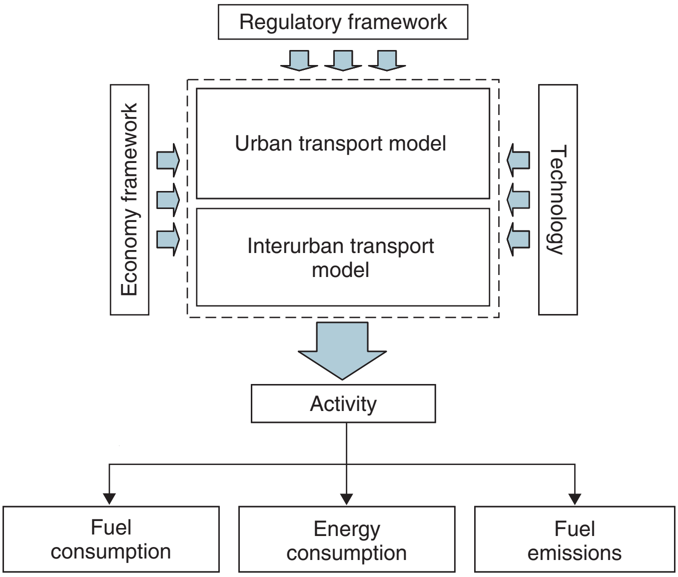

FIGURE 4.2 System network model.

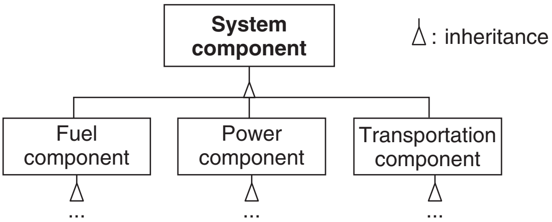

FIGURE 4.3 Object model of the system.

components of its network. For example, the power system is represented by 1-pole and 2-pole elements.

In the list of attributes for each object, there are emission factors in order to estimate their environmental pollution features. The pollutants considered in this work are CO, HC, No*x*, particle material (MP)10, SO_2, CH_4, N_2O, NH_3, and CO_2.

4.4 CLASSES AND OBJECTS RELATIONSHIPS

In this section, a description of the classes together with the interdependencies among them is presented.

4.4.1 Power System Classes

Figure 4.4 shows the hierarchy chart of the power system classes, which corresponds to a simplified version of the hierarchy presented in Ref. [12]. Power component is the most

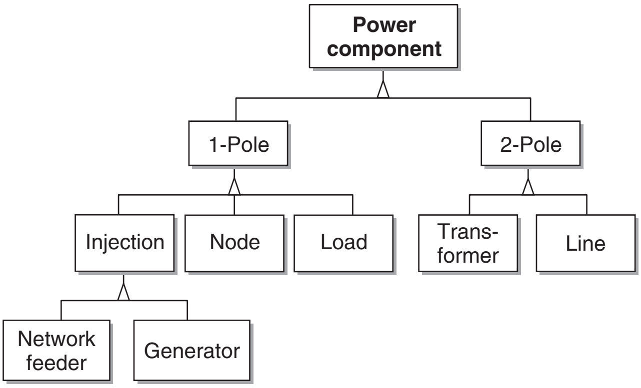

FIGURE 4.4 Hierarchy chart of power system classes.

general class and its attributes and methods are available for all subclasses [10–12]. Since simulation models are typically based on a node/branch-representation, these classes are explicitly included in the OO data model. The *1-pole* subclass encompasses all elements connected between a bus and the neutral (or ground). The subclass *2-pole* contains all branch facilities having impedance such as transmission lines and transformer subclasses. Note that a three winding transformer may be represented by the *2-pole* subclass by using a wye-star transformation. Some Flexible Alternate Current Transmission Systems (FACTS) devices like UPFC can also be modeled through this concept [14].

All the technical parameters of the power system devices are stored in attributes. These attributes include location, economical data, and the set of emission factors.

4.4.2 Hydro Database

Catchment models that are very important in hydrothermal power systems can be incorporated as an additional OO class hierarchy. The set of classes that compound the hydro database (HDB) is depicted in the hierarchy class of Figure 4.5. With it, it is possible to model the hydrographic basin or catchments involved in hydro generation in a simplified way. An inflow of water in a natural regime is characterized by the "natural inflow" class,

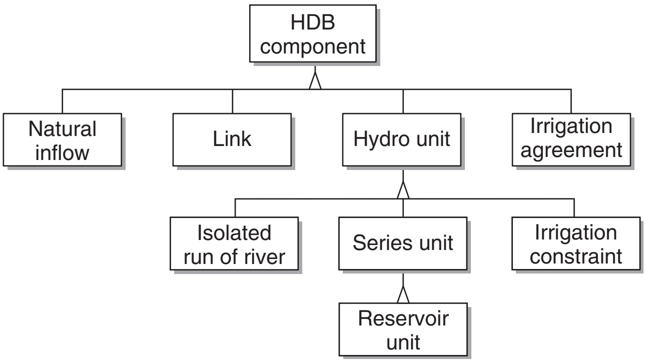

FIGURE 4.5 Hierarchy chart of the hydro database (HDB).

so objects of this kind usually stand at the head of a basin. The "hydro unit" constitutes a decision or an action taken over the water flow, a decision that is specialized in child classes. From the connectivity point of view, the "natural inflow" objects have one output and the "hydro unit" has one input and two output attributes, while the connection between input–output pairs is performed by a "link" object. Following the hierarchy, the "hydro unit" is split into three classes to implement the hydrothermal coordination modeling. While a "series unit" allows full connectivity and could be associated to an network database (NDB's) "generator", an "isolated run of the river" can only receive water from a "natural inflow" and must be associated to a "generator". On the other hand, the "irrigation constraint" class represents extractions from a river course with irrigation purposes, so neither can be related to electrical generation nor can the extractions be the inflow of another object. A more specialized class is the "reservoir unit", which adds to the "series unit" the capability to store water attributes. Finally, an abstract class "irrigation agreement" has been created to include a set of rules that comprise water use rights. An "irrigation agreement" object usually restricts the administration of reservoirs and drives the extractions of "irrigation constraint" based on information such as reservoir storage height, period of the year, and caudal measurements at predefined basin points.

4.4.3 Fuel Network Classes

The hierarchy chart of the fuel network classes is shown in Figure 4.6. Two abstract classes and four final subclasses represent the whole network. A fuel injection system, a storage system, and a customer system can be generalized in a *station* class with common attributes like position and capacity.

A *fuel injection* subclass manages simultaneously different fuel sources in the network. This model can handle 27 different fuel types such as crude oil, city gas, liquefied petroleum gas (LPG), natural gas (NG), gas oil, gasoline (81, 86, 91, 93 lead and unlead), different diesel types, and petcoke.

A *storage object* subclass manages just one of the fuel types. It keeps an initial, current, and final state of stored volume. A more realistic model of a storage can be built with several storage objects.

A *fuel customer* subclass is characterized by the type and amount of each fuel. It can manage simultaneously all possible fuel types coming from the fuel stations.

The *link* represents a union element between two *station* objects. The main attributes are the fuel type, the capacity, and length. Additional *links* are differentiated by the transportation mode of the fuel: pipeline, train, truck, and ship.

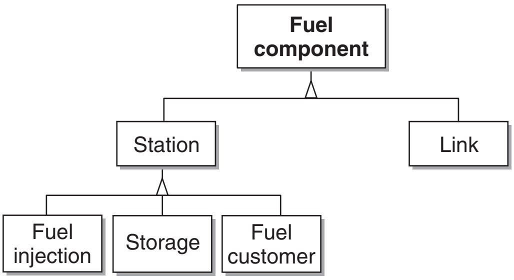

FIGURE 4.6 Hierarchy chart of fuel network classes.

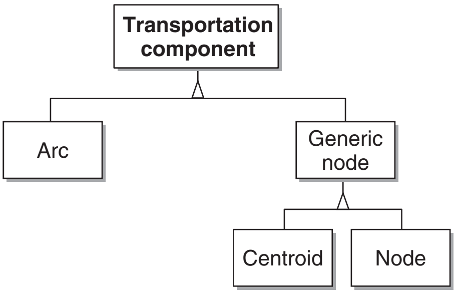

FIGURE 4.7 Hierarchy chart of transportation network classes.

4.4.4 Transportation Network Classes

The hierarchy chart of the transportation network classes defines an *arc* and a *generic node* class. The generic node is further specialized into two classes called *node* and *centroid*, as shown in Figure 4.7.

For transportation networks, a first conceptual separation between urban and interurban networks must be made [15]. A strategic planning study with a national coverage must include an interurban traffic representation. Therefore, in the context of the proposed model, a *centroid* is associated with a conurbation or a vast urban area around and including a large city. The transportation activity of a *conurbation* is stored in attributes, which register the number of attracted and generated travels, the rate of growth, and other relevant parameters.

The *node* component intends to represent only bifurcation and convergence points of transportation ways (with or without population). A *node* either generates or attracts travels. The transportation ways are modeled through a generic class called *Arc*, considering only one-way travels. *Arcs* define capacity, flow, length and speed for each of the following transportation modes: train, electric train, light vehicle, bus, heavy duty vehicle, ship, and plane.

4.4.5 Objects Relationship

One of the main objectives of the proposed modeling is to capture the interdependencies among different sectors. This is accomplished easily by using the classes of each OOP database (power, fuel, and transportation). In fact, a direct relationship between objects, from different databases, occurs through references to objects in the OOP. These references, as shown in Figure 4.8, are given as attributes, of the individual classes. Let us see some examples:

- A combined cycle generating plant is represented as a NG customer in the fuel network.
- Electricity consumption of arcs, centroids, injections, and links of the transportation network are represented by loads in the electric power network.
- Fuel consumption, resulting from the activity of centroids and arcs in transportation networks, is represented by customers in the fuel network.

In the case of HDB, hydro units processed water is electrically generated by generators and/or network feeders from NDB.

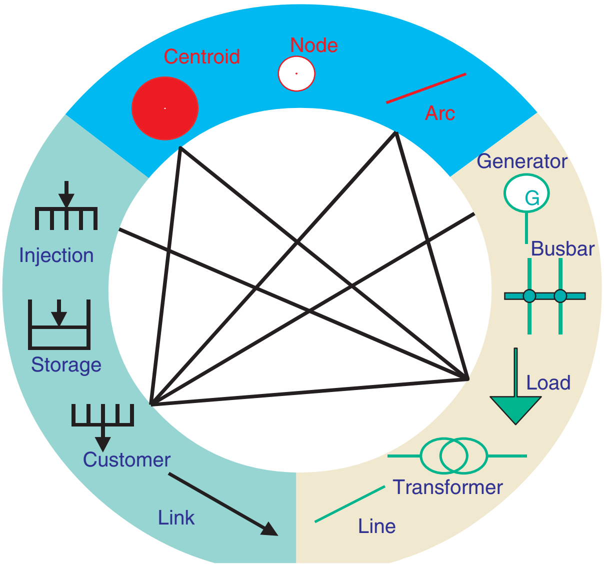

FIGURE 4.8 Physical relationship between objects.

These references define information that is directly available to objects. Thus, the fuel customer “knows” the electrical behavior of a generator, the electrical load “*knows*” the energy consumption of an oil refinery, and so on.

4.5 INFORMATION PLATFORM

On the basis of the preceding models, the PIET (an acronym in Spanish for Transportation and Energy Information Platform) software was developed using Java technology (Fig. 4.9) [10].[1] The OO database (server), which is required by the rest of the platform components, constitutes the core of the application. Source-file and specific power, fuel, and transportation editors allow user interaction with the system information and options.

The gray arrows represent the transmission of required services from clients to their respective servers and the black arrows represent data exchange flows. The design deals with critical aspects of the data management requirements for commercial software and energy companies by building a bridge to existing databases in different source/data file formats.

4.6 SCENARIO DESCRIPTION

The proposed model has the ability to generate, simulate, and analyze global potential scenarios. In this work, we define scenario as a “case study”, expressed in words and numbers, about the way future events and the alternatives can develop. Although uncertainties dominate what really will happen, it is possible to write interesting and believable histories regarding the future.

[1] The final code (around 400 classes) runs efficiently on a Pentium IV computer with 512 MB RAM.

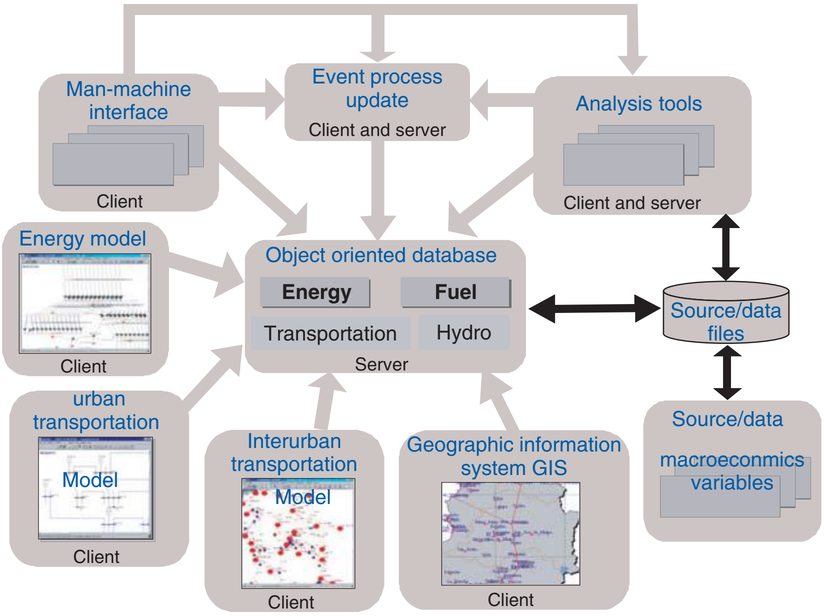

FIGURE 4.9 PIET client-server architecture.

The generation of a scenario usually involves the following steps:

- Defining the limit of space analysis (global, regional, etc.), thematic (sectors to cover, etc.), and temporal (time horizon).
- Describe the current economic, demographic, environmental, and institutional situation.
- Incorporating the driving and conditioning forces of the system and sectors.
- Setting up a narrative that gives the context to the scenario. Often quantitative indicators are used to point out certain aspects.
- Drawing an image of the future. This involves specifying conditions and constraints for one or more points in the time horizon.

The outcome of this procedure is the definition of the following variables: demography, economy, social variables, culture, technology, environment, structures of administration (governance), and infrastructure. These variables work as the entry parameters defining a scenario in PIET. In practical terms, the OO design of PIET allows the following four ways to configure scenarios:

1. Through a direct linking with a *support model*. Support models, refers to those tools (computational programs, rules, databases, etc.) that allow the definition of a scenario. This can be a specific model usually used in the sector (i.e. transportation, energy, or environment) that can provide directly the information for the operation of the PIET.
2. A second alternative is through the use of *activity models* to obtain specific values for variables or entrance parameters to PIET. An example of an activity model is the calculation of fuel price profiles and deviations for a given scenario.

3. By using directly PIET dialogs and frames, that is, objects, system, and tools attributes.
4. Finally, structural changes in networks (for example, the expected generation expansion plan) can be incorporated in PIET by using the respective Editor. Typically it consists of drawing new objects in the networks.

Once the scenario has been incorporated into PIET, specific activity models for each network are run in order to obtain the quantification of interdependencies and the emissions of the scenario. The following studies can be carried out with PIET:

- fuel price variation effects;
- new technology impact;
- effects on energy sector produced by an efficient use of the transportation network;
- identification of network capacity constraints (critical expansion sectors);
- map with possible locations for power plants.

4.7 CASE STUDY EXAMPLE

For a validation of the proposed model, PIET was applied to Chile including the whole national territory. In this case, the hydro network was not considered.

4.7.1 Physical Chilean Networks

The Chilean mainland territory covers an area of 750,000 km^2 with a population of nearly 16 million. Chile has a market-oriented economy characterized by a high level of foreign trade. As a consequence, the electric, fuel, and transportation infrastructure come mainly from private investors. The electricity production was 39.577 billion kWh in 2000, which comprised fossil fuel (51.17%), hydro (46.36%), and others (2.47%). The transmission system, conformed by two main interconnected systems, includes voltage levels up to 500 kV.

NG is imported from neighbor countries using a pipeline system, while fuel and coal arrive in ships from different countries. In summary, the fuel network encompasses a pipeline system of crude oil (755 km), petroleum products (785 km), and NG (320 km).

In the transportation sector, all transport services are privately owned and/or operated with the exceptions of the interurban passenger trains and the urban railroad (Metro). Overall, the railroad system has 6702 km of railways, including 2831 km of broad gauge (1317 km electrified), 117 km narrow gauge (28 km electrified), and 3,754 km of meter gauge (37 km electrified). The highway system covers 79,800 km.

Because of data availability and geographical features of the country, the territory information is described at a province level by 51 zones. Nevertheless, major projects in any network, for example, a new mining site or a new combined cycle unit, are modeled explicitly in the networks (new objects).

In summary, as shown in Table 4.1, the modeling into PIET of the previous described networks (power system, transportation, and fuel network) can be translated in a collection of 1927 objects: 1127 objects are defined for representing the transportation sector, 492 for the electric sector, and 308 for the fuel network.

TABLE 4.1 Objects in the Chilean Case

Power system network	
Number of nodes	103
Number of lines	106
Number of transformers	39
Number of generators	42
Number of loads	202
Total	492
Transportation network	
Number of centroids	272
Number of nodes	183
Number of arcs	672
Total	1127
Fuel network	
Number of fuel injections	20
Number of fuel storages Centers	0
Number of fuel links	257
Number of fuel customers centers	31
Total	308

4.7.2 Network Dependencies

Network dependencies can be classified into two main categories: activity and physical dependencies.

On the one hand, the activity of each network—annual flow (vehicle·km/year) in transportation, annual energy (MWh/year) in electricity sector, and annual consumption (barrel/year or ton/year) in fuel and NG—in the case of Chile can be related with a common set of economic indices. These indices are as follows: gross domestic product (GDP)/year for each province, international and domestic fuel prices, fuel taxes, population (inhabitants/province), and average income. These indices simultaneously shape the behavior of each network.

On the other hand, several physical interactions among the different networks are detected. A diagram with the main physical interdependencies among the networks in the Chilean territory is shown in Figure 4.10.

Figure 4.10 shows that in the whole Chilean territory, there are 133 links among electric, fuel, and transportation networks. As these links are geographically referenced, this information is useful for many purposes such as mapping of pollution in zones, energy consumption, available transfer capabilities of lines, pipelines, and so on.

The national power network is further divided into two main interconnected systems covering the north (Spanish the Northern Interconnected System (SING) with 800 km length) and the central part of the territory (Spanish the Central Interconnected System (SIC) with 2000 km length). As stated before, a major advantage of this representation is that it can be used for planning studies. For example, a new power plant may be drawn in the editor and the impact of this new project is seen inside the power grid and in the fuel network that will provide oil or NG for that plant. In addition, the pollution that this new project will produce will be displayed accordingly.

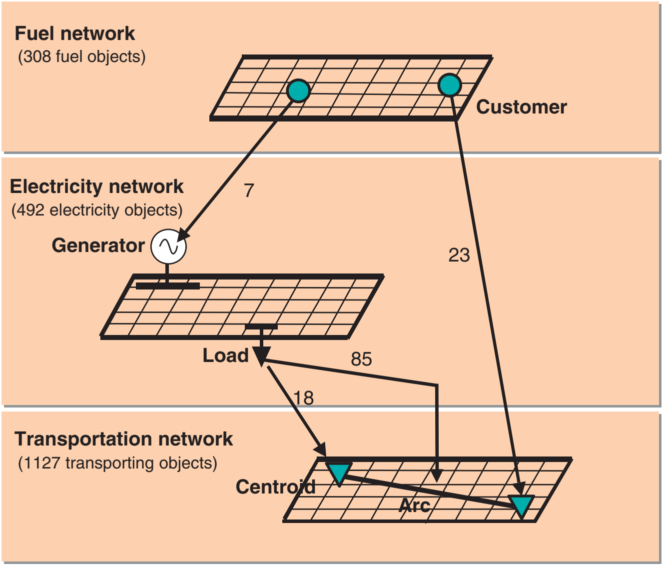

FIGURE 4.10 Diagram with links among sectors.

4.7.3 Specific Activity Models

On the basis of the studies carried out by the government and independent institutions, activity indices and physical dependencies are estimated for each year in the time horizon. A specific activity model is developed for each network.

4.7.3.1 Power Systems. A multinodal, multireservoir dynamic stochastic model, with monthly stages and a time horizon of 10 years is used. Energy production and fuel consumption of each generating unit and their related emissions are obtained. The active power flow pattern for peak demand is computed [10].

4.7.3.2 Transportation. It consists of two interrelated models. The first model encompasses urban transportation, that is, it renders the annual flow (vehicle·km/year) for each transportation mode (train, electric train, light vehicle, bus, and heavy duty vehicle) in any centroid (conurbation in a province).

Most methodologies of calculating urban transportation emissions are based on emissions factors and operational parameters that represent real-world traffic conditions [15–18]. The emissions factors represent emissions of each pollutant as a function of vehicle speed under normal traffic conditions. These factors are obtained experimentally with transient tests conducted on chassis dynamometers with a representative sample of technologies, vehicle types, and driving patterns [19–20]. Operational parameters are a function of link flow densities, average speed, and activity levels measured in kilometer per year per vehicle. These operational parameters are normally obtained from strategic transportation models, traffic surveys, and vehicle fleet databases [20]. However, for long-term and large-scale strategic studies, the data collection and parameter calibration components of these emission estimation methodologies are highly time consuming.

The second model represents the interurban transportation, which estimates the total flow between centroids for each transportation mode. This is a synthetic model that combines generation, distribution, and modal partition in one single stage. Mathematically, it corresponds to an econometric polynomial model.

The total vehicular activity associated with passengers is estimated through a two-stage sequential model that should reach a system-wide equilibrium: generation-attraction (G-A: stage 1) and joint distribution-modal split (D-M: stage 2). Separately, the freight movement is modeled with a direct demand model that simultaneously calculates the trip generation, distribution, and mode choice. The assignment stage in both cases is carried out by a shortest path algorithm on the interurban network.

Because data from Chile is available at the province level, the models are specified at the province level. A province is a subdivision of a larger area called a *region*, and Chile is made up of 15 regions

4.7.3.3 Fuel Network. Fuel consumption is determined by using existing historical data, which is used to adjust a logarithmic model to the activity indices.

4.7.4 Results

A scenario with an electric growth rate of 7%, for years 2003 and 2004, and 8% from year 2005 to 2011, considering hydro and thermal technologies in generation is presented in Figure 4.11. The scenario of Figure 4.11 is built under the assumption that no new hydro projects are carried out. Accordingly, the increase in demand is satisfied mainly by NG generating units.

Simultaneously, the fuel network activity model detects the expected capacity requirements for the pipeline infrastructure. As a consequence of this development, expected emissions increase in the system as shown for the NO*x* case in Figure 4.12.

A summary of the urban transportation activity for the main provinces of the Chilean territory in the year 2002 is shown in Figure 4.13 to show the geographical capability of the model.

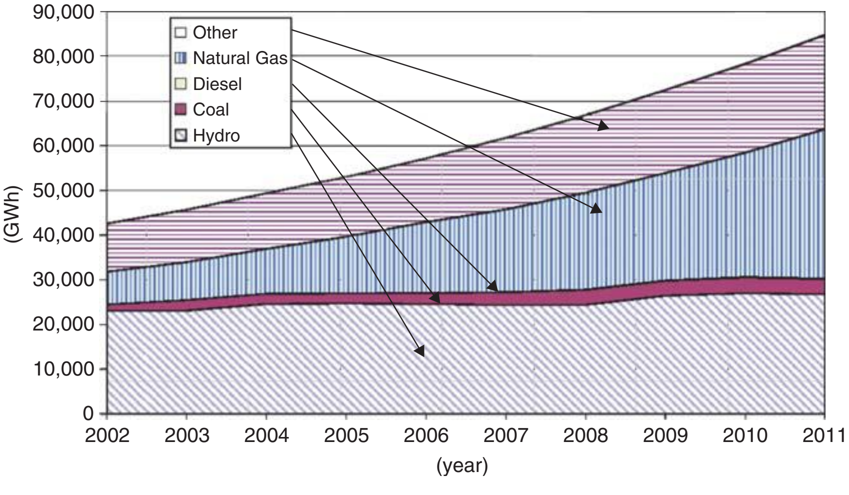

FIGURE 4.11 Annual energy by technology [GWh].

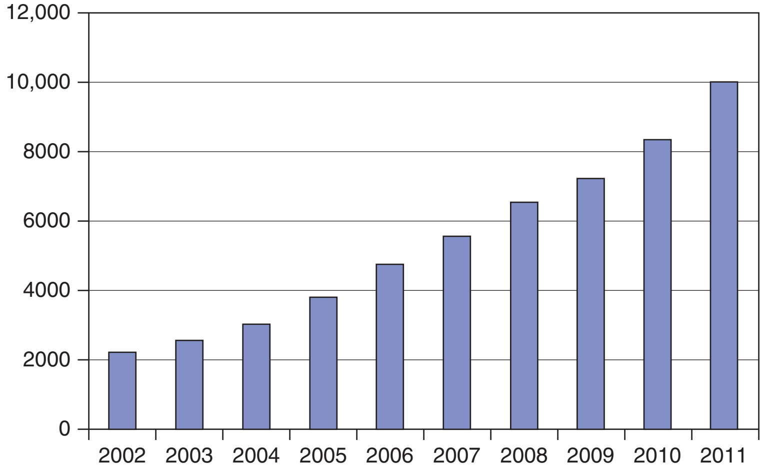

FIGURE 4.12 Annual NO*x* emission in power network [ton/year].

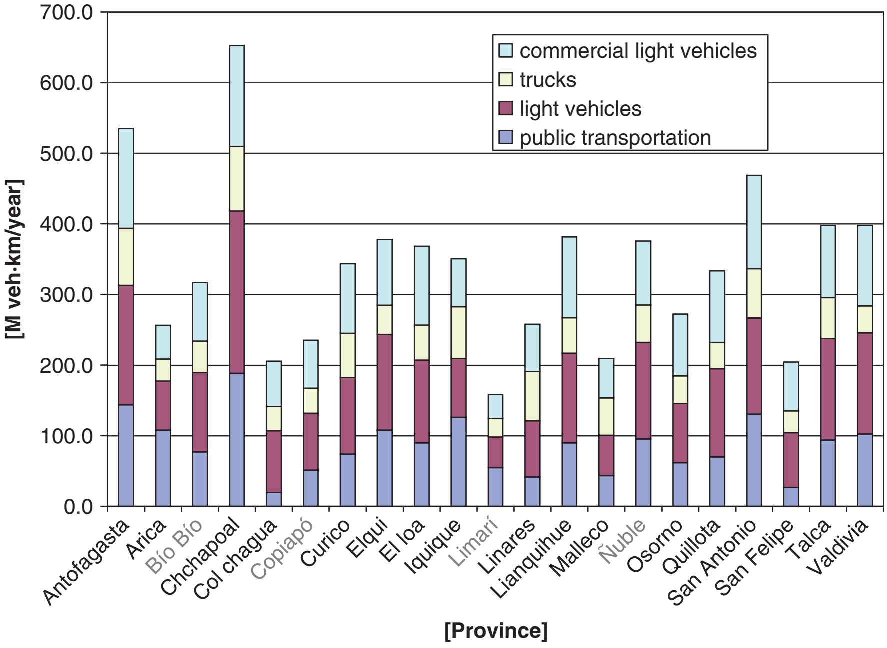

FIGURE 4.13 Transportation activity in year 2002 by technology [M vehicle·km/year].

The corresponding emissions (ton/year) of the transportation activity for MP, NO*x*, HC, and CO are shown in Figure 4.14.

From Figure 4.14 it can be seen that Cachapoal, Iquique, and San Antonio provinces have high degrees of CO emissions, which can be related with public transportation (Fig. 4.13). This suggests that CO and NO*x* mitigation could be achieved by converting the public transportation technology, for instance, to electric vehicles for the whole public

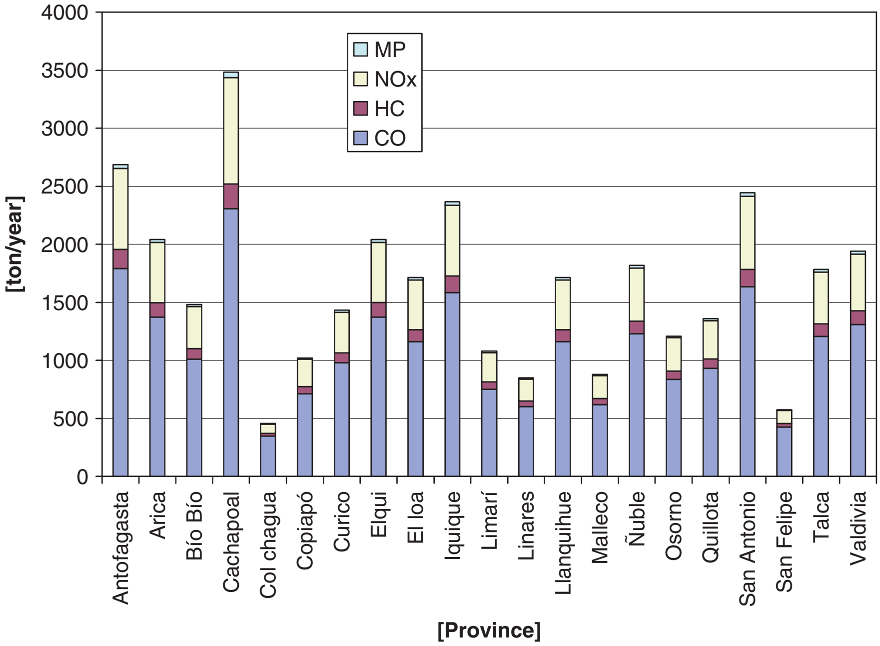

FIGURE 4.14 Transportation emissions in year 2002 [ton/year].

TABLE 4.2 Public Transportation Technology Conversion

Provinces information (base case 2002)	
Public transportation activity	446×10^6 vehicle km/year
Diesel consumption	39×10^6 ga/year
Energy balance after conversion	
Natural gas consumption	$+1716 \times 10^6$ m^3/year
Electric energy generation	+6460 GWh/year
CO and NO*x* balance after conversion	
CO emissions	−4529 ton/year (−89%)
NO*x* emissions	−107 ton/year (−5%)

transportation system. The impact of these changes in the electric and fuel networks is summarized in Table 4.2.

Rows 1–3 of Table 4.2 show the base case information for provinces Cachapoal, Iquique, and San Antonio in year 2002. In these provinces, the public transportation activity is entirely diesel based (39 × 106 ga/year). After the proposed change, diesel consumption is replaced by electric energy, which means an important increase in NG consumption in combined cycle units. In fact, a new combined cycle unit is necessary (400 MW). The conversion scenario achieved a dramatic reduction in CO emission of 89%. In addition, PIET shows that existing NG pipeline system supports the new requirements without new investments.

4.8 CONCLUSION

The OOP approach is useful to perform analysis of energy and transportation networks in the context of strategic planning. OOP and Java technology allow both flexible scenario definitions and a friendly GUI. Thus, a platform like PIET is flexibly adapted as a server structure for the development of several analysis tools. Ongoing research is focused on identifying critical requirements for the energy and transportation infrastructure, and the improvement on activity models for each network and their relationships.

REFERENCES

1. Cole, M. A., and Neumayer, E. (2004). Examining de impact of demographic factors on air pollution. *Popul. Environ.* **26**(1), 5–21.
2. Alson, J., DeCicco, J., Delucchi, M., Greene, D., Johnson, L., McNutt, B., Patterson, P., Santini, D., Sperling, D., and Turrentine, T. (1999). Transportation energy and environmental policy for the 21st century, Asilomar Conference Center, Monterrey, California, pp. 24–27.
3. Delucchi, M. A. (1991). *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity 1*, Center for Transportation Research, Argonne National Laboratory, Argonne, IL. ANL/ESD/TM-22.
4. EIA (2007). Annual energy outlook 2008 with projections to 2030 (Early Release), Report #:DOE/EIA-0383(2008), December 2007.
5. Zografos, K. G., Madas, M. (2003). Optimizing intermodal trip planning decisions in interurban networks, *Proceedings of the 82nd Annual Transportation Research Board Meeting*, January 12–16, 2003, Washington, DC.
6. Handschin, E., Heine, M., König, D., Nikodem, T., Seibt, T., and Palma, R., (1998). Object-oriented software engineering for transmission planning in open access schemes. *IEEE T. Power Syst.* **13**(1), 94–100.
7. Palma R., Moya, O., and Vargas, L. (2001). Object-oriented simulation software for a competitive environment—application to transmission expansion planning, *The First EPRI Latin American Conference & Exhibition: Toward a Mature Electricity Market Through Technology, R&D, and Business Vision*, *Rio de Janeiro*, Brasil, 28–30 November, 2001.
8. Department of Energy—DOE , White House Office of Science and Technology Policy-OSTP (2000). Workshop on Infrastructure Interdependencies Research and Development Workshop, McLean, IL, June, 2000.
9. York, R., Rosa, E. A., and Dietz, T. (2003). STIRPAT, IPAT and ImPACT: analytical tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* **46**(3), 351–365.
10. Palma, R., Vargas, L., Flatow, F., and Oyarce, N. (2003). Object oriented platform for an integrated analysis of energy and transportation networks. *IEEE T. Power Syst.* **18**, 1062–1069.
11. Rumbaugh, J., Jacobson, I., and Booch, G. (2004). *The Unified Modeling Language reference manual*, 2nd Ed. Addison-Wesley Professional, Boston, Massachusetts, ISBN: 0321245628.
12. UML Resource Page of the Object Management Group (2008). *Resources that Include the Latest Version of the UML Specification*. Available at http://www.uml.org/.
13. Foley, M., Bose, A., Mitchell, W., and Faustini, A. (1993). An object based graphical user interface for power systems. *IEEE T. Power Syst.*, **8**(1), 97–104.
14. Palma-Behnke, R., Vargas, L. S., Pérez, J. R., Núñez, J., and Torres, R. A. (2004). OPF with SVC and UPFC modeling for longitudinal systems. *IEEE T. Power Syst.* **19**(4), 1742–1753.
15. Lyons, T. J., Kenworthy, J. R., Moy, C., and Dos Santos, F. (2003). An international urban air pollution model for the transportation sector. *Transport. Res. D-Tr. E.* **8**, 159–167.

16. Sharma, P., and Khare, M. (2001). Modelling of vehicular exhaust—a review. *Transport. Res. D-Tr. E.* **6**, 179–198.
17. Zachariadis, T., and Zamaras, Z. (1999). An integrated modeling system for estimation of motor vehicle emissions. *J. Air Waste Manage. Assoc.* **49**, 1010–1026.
18. Corvalán, R. M., Osses, M., Urrutia, C. M., and Gonzalez, P. A. (2005). Estimating traffic emissions using demographic and socio-economic variables in 18 chilean urban areas. *Popul. Environ.* **27**(1), 63–87.
19. Ntziachristos, L., Samaras Z., Eggleston, S., Goriben, N., Hasse, l. D. Hickman, J., Joumard, R., Rijkeboer, R., and Zierock, H. (1999). *Computer Programme to Calculate Emissions from Road Transport, COPERT III. Methodology and Emission Factors*. European Environmental Agency. European Topic Centre on Air Emission, Thessaloniki.
20. De Cea, J., Fernández, E., Dekock, V., Soto, A., and Friez, T. (2003). ESTRAUS: a computer package for solving suplí-demand equilibrium problems on multimodal urban transportation networks with multiple user classes, *Proceedings of Transportation Research Board Annual Meeting*, Washington, DC, January 2003 (CD-ROM).

FURTHER READING

Bakkes, J. (2000). Global Dynamics and Sustainable Development Programme, RIVM Report no. 402001018, October 2000.

5

SELF-HEALING AND RESILIENT ENERGY SYSTEM

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5.1 INTRODUCTION

The rise of our nation into a global economic power, which began with the opening of a vast continent in the mid-1800s by the railroads, was followed in the nineteenth century by expansion of the networks of commerce, navigable waterways, transportation, water supply and wastewater, dams, electric power networks, and rural electrification (in the early to mid-twentieth century), aviation, transit, and highways. This has dramatically transformed our nation and the resultant economic output has been unprecedented in history.

The tremendous value of infrastructure systems such as roads and bridges and the nation that help make possible indispensable activities of our modern societies cannot be overstated. I would submit that along with our bricks and mortar infrastructure—railroads, highways, bridges, seaports, and airports—another important part is the "hidden infrastructure" that supports the workings of all aspects of our $14 trillion economy.[2]

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[2] A 24-page special feature in *The Wilson Quarterly* for Spring 2008 (Vol. 32, No. 2) includes three articles under the heading, "BACKBONE: Infrastructure for America's Future." The three are "The Secret Is the System," "Get Smart," and "Built to Last." An introduction notes that "building tomorrow's infrastructure will pose larger political and technological challenges than ever before-with potential payoffs to match." Examples cited are the huge new water tunnel being dug beneath New York City, started in 1970 and to be completed by 2020; the collapse of the I-35W bridge in Minneapolis, the 2003 blackout affecting 50 million people, and the proposed North American Super Corridor, from Mexico to Canada that would create a road, rail, and shipping system around the existing I-35. Some excerpts: Shopping for Infrastructure The American Society of Civil Engineers *Report Card for America's Infrastructure* (2005) offers a daunting menu of future needs and calls for more than $300 billion in additional annual spending (for more information please see http://www.wilsoncenter.org/index.cfm).

Energy Systems Security, Edited by John G. Voeller

5.2 THE BIGGER PICTURE

Energy, telecommunications, transportation, and financial infrastructures are becoming increasingly interconnected, thus posing new challenges for their secure, reliable, and efficient operation. All of these infrastructures are themselves complex networks, geographically dispersed, nonlinear, and interacting both among themselves and with their human owners, operators, and users. No single entity has complete control of these multiscale distributed, highly interactive networks, nor does any such entity have the ability to evaluate, monitor, and manage them in real time. In fact, the conventional mathematical methodologies that underpin today's modeling, simulation, and control paradigms are unable to handle the complexity and interconnectedness of these critical infrastructures.

Power, telecommunications, banking and finance, transportation and distribution, and other infrastructures are becoming more and more congested partially due to dramatic population growth, particularly in urban centers. These infrastructures are increasingly vulnerable to failures cascading through and between them. A key concern is the avoidance of widespread network failure due to cascading and interactive effects. Moreover, interdependence is only one of several characteristics that challenge the control and reliable operation of these networks. Other factors that place increased stress on the power grid include dependencies on adjacent power grids (increasing because of deregulation), telecommunications, markets, and computer networks. Furthermore, reliable electric service is critically dependent on the whole grid's ability to respond to changed conditions instantaneously.

Secure and reliable operation of complex networks poses significant theoretical and practical challenges in analysis, modeling, simulation, prediction, control, and optimization. The pioneering initiative in the area of complex interactive networks and infrastructure interdependency modeling, simulation, control, and management was launched and successfully carried out during 1998–2002, through the Complex Interactive Networks/Systems Initiative (CIN/SI). It studied closely the challenges to the interdependent electric power grid, energy, sensing and controls, communications, transportation, and financial infrastructures.

It comprised six university research groups consisting of 108 university faculty members and over 220 researchers who were involved in the joint Electric Power Research Institute (EPRI) and US Department of Defense program. During 1998–2002, CIN/SI developed modeling, simulation, analysis, and synthesis tools for damage-resilient control of the electric power grid and interdependent infrastructures connected to it. This work showed that the grid can be operated close to the limit of stability given adequate situational awareness combined with better security of communications and controls. A grid operator is similar to a pilot flying an aircraft as in monitoring how the system is being affected, how the "environment" is affecting it, and having a solid sense of how to steer it in a stable fashion.

In recent decades, in light of increased demand, we have reduced the generation and transmission capacity margins of the electric power grid, and we are indeed flying closer to the edge of the stability envelope. Ongoing programs at EPRI, Department of Energy (DOE) are continuing pursuit of these objectives.

Earlier work by the author during the 1990s on damaged F-15 aircraft in part, provided background for the creation, successful launch, and management of research programs for the electric power industry, including the EPRI/DOD CIN/SI mentioned above, which involved six university research consortia along with two energy companies, to address challenges posed by our critical infrastructures. This work was done during the period from 1998 to early 2002. CIN/SI laid the foundation for several ongoing initiatives on the self-healing infrastructure and subsets focusing on smart reconfigurable electrical networks. These have now been under development for some time at several organizations, including programs sponsored by the National Science Foundation (NSF), DOD, DOE, and EPRI (including the "Intelligrid" program), and the US DOE's "Gridwise" and "Modern Grid" initiative.

To provide a context for this, the EPRI/DOD CIN/SI aimed to develop modeling, simulation, analysis, and synthesis tools for robust, adaptive, and reconfigurable control of the electric power grid and infrastructures connected to it. In part, this work showed that the grid can be operated close to the limit of stability given adequate situational awareness combined with better sensing of system conditions and communication controls. A grid operator steers it in a stable fashion by keeping the lines within their operating limits while helping a instantaneous balance between loads (demand) and available generation. Grid operators often make these quick decisions under considerable stress. Given that in recent decades we have reduced the generation and transmission capacity, we are indeed flying closer to the edge of the stability envelope.

As an example, one aspect of the Intelligrid program is aimed at enabling grid operators have greater look-ahead capability and foresight, overcoming limitations of the current schemes which at best have over a 30-seconds' delay in assessing system behavior. This is analogous to driving to the car by looking into the rear-view mirror instead of the road ahead. This tool using advanced sensing, communication, and software module was proposed during 2000 to 2001 and the program was initiated in 2002 by the author while at EPRI, under the Fast Simulation and Modeling (FSM) program. This advanced simulation and modeling program promotes greater grid self-awareness and resilience in times of crisis, in three ways: by providing faster-than-real-time, look-ahead simulations (analogous to master chess players rapidly expanding and evaluating their various options under time constraints) and thus avoiding previously unforeseen disturbances; by performing what-if analysis for large-region power systems from both operations and planning points of view; and by integrating market, policy, and risk analysis into system models, and quantifying their integrated effects on system security and reliability.

5.3 INFRASTRUCTURES UNDER THREAT

The terrorist attacks of September 11th exposed critical vulnerabilities in America's essential infrastructures: never again can the security of these fundamental systems be taken for granted. Electric power systems constitute *the* fundamental infrastructure of modern society. A successful terrorist attempt to disrupt electricity supplies could have devastating effects on national security, the economy, and the life of every citizen. Yet, power systems have widely dispersed assets that can never be absolutely defended against a determined attack.

The growing potential for infrastructural problems stems from multiple sources, including system complexity, deregulation, economic effects, power market impacts, and human error. The existing power system is also vulnerable to natural disasters and intentional attacks (terrorism). Regarding the latter, a November 2001 EPRI assessment developed in response to the September 11th attacks highlights three kinds of potential threats to the US electricity infrastructure.

We discuss them briefly and in very broad terms, without providing a "blue book" for potential attackers: The first is attacks *upon* the power system. In this case, electricity infrastructure is the primary target—with ripple effects, in terms of outages extending into the customer base. The point of attack could be a single component, such as a critical substation or a transmission tower. There could also be a simultaneous, multipronged attack intended to bring down the entire grid in a specific region of the United States An attack could also target electricity markets which are highly vulnerable because of their transitional status.

The second type of attack is *by* the power system. In this case the ultimate target is the population, using parts of the electricity infrastructure as a weapon—similar to the way our transportation and mail delivery systems were used against our nation. Power plant cooling towers, for example, could be used to disperse chemical or biological agents.

The third means is attack *through* the power system. In this case, the target is the civil infrastructure. Utility networks include multiple conduits for attack, such as lines, pipes, underground cables, tunnels, and sewers. An electromagnetic pulse, for example, could be coupled through the grid with the intention of damaging computer and/or telecommunications infrastructure.

As seen from these scenarios, the specter of terrorism raises a profound dilemma for the electric power industry: How to make the electricity infrastructure more secure without compromising productivity in today's complex, highly interconnected electric networks? Resolving this dilemma requires short-term and long-term technology development and deployment, affecting fundamental characteristics of today's power systems.

The North American electric power system needs a comprehensive strategy to prepare for the diverse threats posed by terrorism. Such a strategy should both increase protection of vital industry assets and assure the public that they are well protected. A number of actions will need to be considered in formulating an overall security strategy:

- The grid must be made secure from cascading damage.
- Pathways for environmental attack must be sealed off.
- Conduits for attack must be monitored, sealed off, and "sectionalized" under attack conditions.
- Critical controls and communications must be made secure from penetration by hackers and terrorists.
- Greater intelligence must be built into the grid to provide flexibility and adaptability under attack conditions, including automatic reconfiguration.
- Ongoing security assessments, including use of game theory to develop potential attack scenarios, will be needed to ensure that the power industry can stay ahead of changing vulnerabilities.

A survey of electric utilities revealed real concerns about grid and communications security on the perceived threats to utility control centers. The most likely threats were bypassing controls, integrity violations, and authorization violations, with four-in-ten rating each as either a 5 or 4, out of 5. Concern about potential threats generally increased as the size of the utility (peak load) increased.

The system's equipment and facilities are dispersed throughout the North American continent, which complicates absolute protection of the system from a determined terrorist attack. In addition, another complexity needs to be considered—the power delivery systems' physical vulnerabilities, and susceptibility to disruptions in computer networks and communication systems. For example, terrorists might exploit the increasingly centralized control of the power delivery system to magnify effects of a localized attack. Because many consumers have become more dependent on electronic systems that are sensitive to power disturbances, an attack that leads to even a momentary interruption of power can be costly. A 20-min outage at an integrated circuit fabrication plant, for example, could cost US$30 million.

The Grid Then and Now

The first grids. The worldwide electrical grid deployment, now costing trillions of dollars and reaching billions of people, began very humbly. The first grids came into being in the 1880s, for bringing electrical energy to a variety of customers for a variety of uses; at first mostly for illumination but later for turning power machines and moving trolley cars. The most important of these early grids, the first established big city grid in North America, was the network built by Thomas Edison in lower Manhattan. From its power station on Pearl Street, practically in the shadow of the Brooklyn Bridge, Edison's company supplied hundreds and then thousands of customers. Shortly thereafter, Edison's patented devices, and those of his competitors—devices such as bulbs, switching devices, generators, and motors—were in use, in new grids in towns all over the industrialized world.

Grid Overview

- Power, communications, and computing are all converging, making entire systems as sensitive as the most sensitive component.
- Secure and reliable combined electric power, communications, fuel supply, and financial networks are essential to today's microprocessor-based economy, public health and safety, and overall quality of life.
- The demands of our secure digital economy are outpacing the electricity and communication infrastructures that support it.
- It costs the United States $75–180 billion in annual losses from power outages and disturbances. On any day, typically half a million people are without power for 2 or more hours.
- The US power grid operates under ever more stress from increasing electrical traffic and from a changing economic climate. Here are four notable grid issues: (i) the regulatory problem: federal and state grid guidelines often conflict; (ii) the investment problem: demand for power is increasing faster than new grid construction; (iii) the reliability problem: operating rules should keep the grid up and running more of the time; (iv) the marketplace problem: in many instances, the production, transmission, and distribution of power is subject to unfair competition.

- Operating the grid will increasingly come to resemble the flight of combat aircraft, including the use of complex adaptive software.

Smart Self-Healing Grid

- What is “self-healing?”
  - A system that uses information, sensing, control and communication technologies to allow it to deal with unforeseen events and minimize their adverse impact.
- Why is self-healing concept important to the energy infrastructure?
  - It is a secure “architected” sensing, communications, automation (control), and energy-overlaid infrastructure as an integrated, reconfigurable, and electronically controlled system that will offer unprecedented flexibility and functionality. It will also improve system availability, security, quality, resilience and robustness.

5.4 A STRESSED INFRASTRUCTURE

The major outage on 14 August 2003, in the eastern United States and the earlier California power crisis in 2000–2001 are only the most visible parts of a larger and growing US energy crisis from inadequate investments in the infrastructure, leading to a fundamental imbalance between growing demand and an almost stagnant supply. The imbalance had been brewing for many years and is prevalent throughout the nation.

From a broader view, the North American electricity infrastructure is vulnerable to increasing stresses from several sources. One stress is caused by an imbalance between growth in demand for power and enhancement of the power delivery system to support this growth. From 1988 to 1998, the United States’ electricity demand rose by nearly 30%, but the capacity of its transmission network grew by only 15%. This disparity is likely to increase from 1999 to 2009: analysts expect demand to grow by 20%, while planned transmission systems grow by only 3.5%. Along with that imbalance, today’s power system has several sources of stress:

- *Demand is Outpacing Infrastructure Expansion and Maintenance Investments.* Generation and transmission capacity margins are shrinking and unable to meet peak conditions particularly when multiple failures occur, while electricity demand continues to grow.
- *The Transition to Deregulation is Creating New Demands That Are Not Being Met.* The electricity infrastructure is not being expanded or enhanced to meet the demands of wholesale competition in the industry; so connectivity between consumers and markets is at a gridlock.

- *The Present Power Delivery Infrastructure Cannot Adequately Handle Those New Demands of High End Digital Customers and Twenty-First-Century Economy.* It cannot support the levels of security, quality, reliability, and availability needed for economic prosperity.
- *The Infrastructure Has Not Kept Up with New Technology.* Many distribution systems have not been updated with current technology including IT.
- *Proliferation of Distributed Energy Resources (DERs).* DER includes a variety of energy sources—microturbines, fuel cells, photovoltaics, and energy storage devices—with capacities from approximately 1 kW to 10 MW. DER can play an important role in strengthening energy infrastructure. Currently, DER accounts for about 7% of total capacity in the United States, mostly in the form of backup generation, yet very little is connected to the power delivery system. By 2020, DER could account for as much as 25% of total US capacity, with most DER devices connected to the power delivery system.
- *Return on Investment(ROI) Uncertainties Are Discouraging Investments in the Infrastructure Upgrades.* Investing new technology in the infrastructure can meet these aforementioned demands. More specifically, according to a June 2003 report by the NSF, R&D spending in the United States as a percent of net sales was about 10% in the computer and electronic products industry and 12% for the communication equipment industry in 1999. Conversely, R&D investment by electric utilities was less than 0.5% during the same period. R&D investment in most other industries is also significantly greater than that in the electric power industry.
- *Concern about the National Infrastructure's Security (1).* A successful terrorist attempt to disrupt electricity supplies could have devastating effects on national security, the economy, and human life. Yet power systems have widely dispersed assets that can never be absolutely defended against a determined attack.

Competition and deregulation have created multiple energy producers that share the same energy distribution network, one that now lacks the carrying capacity or safety margin to support anticipated demand. Investments in maintenance, and research and development continue to decline in the North American electrical grid. Yet, investment in core systems and related IT components are required to ensure the level of reliability and security that users of the system have come to expect.

From a national security viewpoint, in the aftermath of the tragic events of September 11th and recent natural disasters and major power outages, there are increased national and international concerns about the security, resilience and robustness of critical infrastructures in response to evolving spectra of threats. Secure and reliable operation of these networks is fundamental to national and international economy, security and quality of life[3].

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[3] Executive Order 13010, signed by President Clinton in 1996, defined critical infrastructures as "so vital that their incapacity or destruction would have debilitating impact on the defense or economic security of the United Stares" and included "telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water-supply systems, emergency services and continuity of government." The US Department of Homeland Security (DHS) in the National Infrastructure Protection Plan has expanded the concept to include "key resources" and added food and agriculture, health and health care, defense industrial base, information technology, chemical manufacturing, postal and shipping, dams (including locks and levees), government facilities, commercial facilities, and national monuments and icons. The National Infrastructure

5.5 WHERE ARE WE AND HOW DID WE GET HERE?

The existing electricity infrastructure evolved to its technology composition today from the convolution of several major forces, only one of which is technologically based. Today opportunities and challenges persist in worldwide electric power networks, these include: reducing transmission congestion, increasing system/cyber security, increasing overall system and end-use efficiency while maintaining reliability, and so on. Many other challenges engage those who plan for the future of the power grid: producing power in a sustainable manner (embracing renewable fuels while accounting for their scalability limitations, for example, increased use of land and natural resources to produce more renewable electricity will not be sustainable, thus not being able to lower emissions from existing generators), delivering electricity to those who do not have it (not just on the basis of fairness but also because electricity is the most efficient form of energy, especially for things like lighting), and using electricity more wisely as a tool of economic development, and pondering the possible revival of advanced nuclear reactor construction. To prepare for a more efficient, resilient, secure and sustainable electrical system it is helpful to remember the historical context, associated bottlenecks and forcing functions:

As the readers of this chapter know, the trends of worldwide electrical grid deployment, costing trillions of dollars and reaching billions of people, began very humbly. Some obvious electrical and magnetic properties were known in antiquity. In the seventeenth and eighteenth centuries, partially through scientific experiments and partially through parlor games, more was learned about how electric charge is conducted and stored. But only in the nineteenth century, with the creation of powerful batteries, and through insights about the relations between electric and magnetic force could electricity in wires service large-scale industries—first the telegraph and then telephones.

And only in the 1880s did the first grids come into being for bringing electrical energy to a variety of customers for a variety of uses, at first mostly for illumination but later for turning power machines and moving trolley cars. The most important of these early grids, the first established big city grid in North America, was the network built by Thomas Edison in lower Manhattan. From its power station on Pearl Street, practically in the shadow of the Brooklyn Bridge, Edison's company supplied hundreds and then thousands of customers. Shortly thereafter, Edison's patented devices, and those of his competitors—devices such as bulbs, generators, switching devices, generators, and motors—were in use in new grids in towns all over the industrialized world.

From a historical perspective the electric power system in the United States evolved in the first half of the twentieth century without a clear awareness and analysis of the system-wide implications of its evolution. In 1940, 10% of the energy consumption in America was used to produce electricity. By 1970, this had risen to 25%, and by 2002 it had risen to 40%. (Worldwide, current electricity production is near 15,000 billion kWh/year, with the United States, Canada, and Mexico responsible for about 30% of this consumption.) This grid now underlies every aspect of our economy and

Improvement Act (S. 1926) defines "infrastructure" as any of a number of components of the transportation system, water supply and control facilities, resource recovery facilities, and solid waste disposal facilities." While in our research we focus on a subset of (i) energy and power, (ii) cyber and telecommunications, (iii) transportation, (iv) banking and finance, and their couplings and interdependencies; elsewhere in our nation, all the 17 sectors identified by DHS are under study by the ASME, DHS, National Labs, and other organizations.

society, and it has been hailed by the National Academy of Engineering as the twentieth century's engineering innovation that has been most beneficial to our civilization. The role of electric power has grown steadily in both scope and importance during this time and electricity is increasingly recognized as a key to societal progress throughout the world, driving economic prosperity, security and improving the quality of life. Still it is noteworthy that at the time of this writing, there are about 1.4 billion people in the world with no access to electricity, and another 1.2 billion people have inadequate access to electricity (meaning that they experience outages of 4 h or longer per day).

Once "loosely" interconnected networks of largely local systems, electric power grids increasingly host large-scale, long-distance wheeling (movement of wholesale power) from one region or company to another. Likewise, the connection of distributed resources, primarily small generators at the moment, is growing rapidly. The extent of interconnectedness, like the number of sources, controls, and loads, has grown with time. In terms of the sheer number of nodes, as well as the variety of sources, controls, and loads, electric power grids are among the most complex networks made.

In the coming decades, electricity's share of total energy is expected to continue to grow, as more efficient and intelligent processes are introduced into this network. Electric power is expected to be the fastest-growing source of end-use energy supply throughout the world. To meet global power projections, it is estimated by the US DOE/EIA that over $1 trillion will have to be spent during the next 10 years. The electric power industry has undergone a substantial degree of privatization in a number of countries over the past few years. Growth in power generation capacity is expected to be particularly strong in the rapidly growing economies of Asia, with China leading the way.

The electric power grid's emerging issues include: creating distributed management through using distributed intelligence and sensing; integration of renewable resources; use of active-control high voltage devices; developing new business strategies for a deregulated energy market; and ensuring system stability, reliability, robustness, and efficiency in a competitive marketplace and carbon-constrained world.

In addition, the electricity grid faces (at least) three looming challenges: its organization, its technical ability to meet 25-year and 50-year electricity needs, and its ability to increase its efficiency without diminishing its reliability and security.

As an example of historical bifurcation points, the 1965 Northeast blackout not only brought the lights down, it also marked a turn in grid history. The previous economy of scale, according to which larger generators were always more efficient than small machines, no longer seemed to be the only risk-managed option. In addition, in the 1970s two political crises—the Middle East war of 1973 and the Iranian Revolution in 1979—led to a crisis in fuel prices and a related jump in electric rates. For the first time in decades, demand for electricity stopped growing. Moreover, the prospects of power from nuclear reactors, once so promising, now faced public resistance and the resultant policy threats. Accidents at Brown's Ferry, Alabama in 1974 and Three Mile Island, Pennsylvania in 1979, and rapidly escalating construction costs caused a drastic turnaround in orders for new facilities. Some nuclear plants already under construction were abandoned.

In the search for a new course of action, conservation (using less energy) and efficiency measures (to use available energy more wisely) were put into place. Electrical appliances were reengineered to use less power. For example, while on the average today's refrigerators are about 20% larger than those made 30 years ago, they use less than half the electricity of older models. Furthermore, the Public Utility Regulatory Policy Act (PURPA) of 1978 stipulated that the main utilities were required to buy the power produced by certain independent companies which cogenerated electricity and heat with great efficiency, providing the cost of the electricity was less than the cost it would take the utilities to make it for their own use.

What had been intended as an effort to promote energy efficiency, turned out, in the course of the 1980s and 1990s, to be a major instigator of change in the power industry as a whole. First, the independent power producers increased in size and in number. Then they won the right to sell power not only to the neighboring utility but also to other utilities further away, often over transmission lines owned by other companies. With the encouragement of the Federal Energy Regulatory Commission (FERC), utilities began to sell off their own generators. Gradually the grid business, which for so long had operated under considerable government guidelines since so many utilities were effective monopolies, became a confusing mixture of regulated and unregulated companies.

Opening up the power industry to independent operators, a business reformation underway for some years in places like Chile, Australia, and Britain (where the power denationalization process was referred to as “liberalization”), proved to be a bumpy road in the United States. For example, in 2001 in the state of California, the effort to remove government regulations from the sale of electricity, even at the retail level, had to be rescinded in the face of huge fluctuations in electric rates, rolling blackouts, and amid allegations of price-fixing among power suppliers. Later that year, Enron, a company that had grown immense through its pioneering ventures in energy trading and providing energy services in the new freed-up wholesale power market, declared bankruptcy.

Restructuring of the US power grid continues. Several states have put deregulation into effect in a variety of ways. New technology has helped to bring down costs and to address the need for reducing emission of greenhouse gases during the process of generating electricity. Examples include high efficiency gas turbines, integrated “microgrids” of small generators (sometimes in the form of solar cells or fuel cells), and a greater use of wind turbines.

Much of the interest in restructuring has centered around the generation part of the power business and less on expanding the transmission grid itself. About 25 years ago, the generation capacity margin, the ability to meet peak demand, was between 25 and 30%. It has now reduced to less than half and is currently at about 10–15%. These “shock absorbers” have been shrinking; for example, during the 1990s actual demand in the United States increased by some 35%, while transmission capacity has increased by only 18%. In the current decade, the demand is expected to grow by about 20%, with new transmission capacity lagging behind at under 4% growth.

In the past, extra generation capacity served to reduce the risk of generation shortages in case equipment failed and had to be taken out of production, or in case there was an unusually high demand for power, such as on very hot or cold days. As a result capacity margins, both for generation and transmission, are shrinking. Other changes add to the pressure on the national power infrastructure as well. Increasing interregional bulk power transactions strain grid capacity. New environmental considerations, energy conservation efforts, and cost competition require greater efficiency throughout the grid.

As a result of these “diminished shock absorbers,” the network is becoming increasingly stressed, and whether the carrying capacity or safety margin will remain to support anticipated demand is in question. The most visible parts of a larger and growing US energy crisis is the result of years of inadequate investments in the infrastructure. The reason for this neglect is caused partly by uncertainties over what government regulators will do next and what investors will do next.

Growth, environmental issues, and other factors contribute to the difficult challenge of ensuring infrastructure adequacy and security. Not only are infrastructures becoming more complexly interwoven and more difficult to comprehend and control, there is less investment available to support their development. Investment is down in many industries. For the power industry, direct infrastructure investment has declined in an environment of regulatory uncertainty due to deregulation, and infrastructure R&D funding has declined in an environment of increased competition because of restructuring. Electricity investment was not large to begin with. Presently the power industry spends a smaller proportion of annual sales on R&D than do the dog foods, leather, insurance, or many other industries—less than 0.3% or about $600 million per year.

Most industry observers recognize this shortage of transmission capability, and indeed many of the large blackouts in recent years can be traced to transmission problems, either because of faults in the lines themselves or in the coordination of power flow over increasingly congested lines. However, in the need to stay "competitive," many energy companies, and the regional grid operators that work with them, are "flying" the grid with less and less margin for error. This means keeping costs down, not investing sufficiently in new equipment, and not building new transmission highways to free up bottlenecks.

5.6 CHIEF GRID PROBLEMS

Several cascading failures during the past 40 years have spotlighted our need to understand the complex phenomena associated with power network systems and the development of emergency controls and restoration. In addition to the mechanical failures, overloading a line can create power-supply instabilities such as phase or voltage fluctuations. For an AC power grid to remain stable, the frequency and phase of all power generation units must remain synchronous within narrow limits. A generator that drops 2 Hz below 60 Hz will rapidly build up enough heat in its bearings to destroy itself. So circuit breakers trip a generator out of the system when the frequency varies too much. But much smaller frequency changes can indicate instability in the grid: in the Eastern Interconnect, a 30 MHz drop in frequency reduces power delivered by 1 GW.

According to data from the North American Electric Reliability Corporation (NERC) and analyses from the EPRI, average outages from 1984 to the present have affected nearly 700,000 customers per event annually. Smaller outages occur much more frequently and affect tens to hundreds of thousands of customers every few weeks or months, while larger outages occur every two to nine years and affect millions. Much larger outages affect seven million or more customers per event each decade. These analyses are based on data collected for the US DOE, which requires electric utilities to report system emergencies that include electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of bulk power delivery systems, and fuel problems.

Coupling these analyses with diminished infrastructure investments, and noting that the cross-over point for the utility construction investment versus depreciation occurred in 1995, we analyzed the number and frequency of major outages along with the number

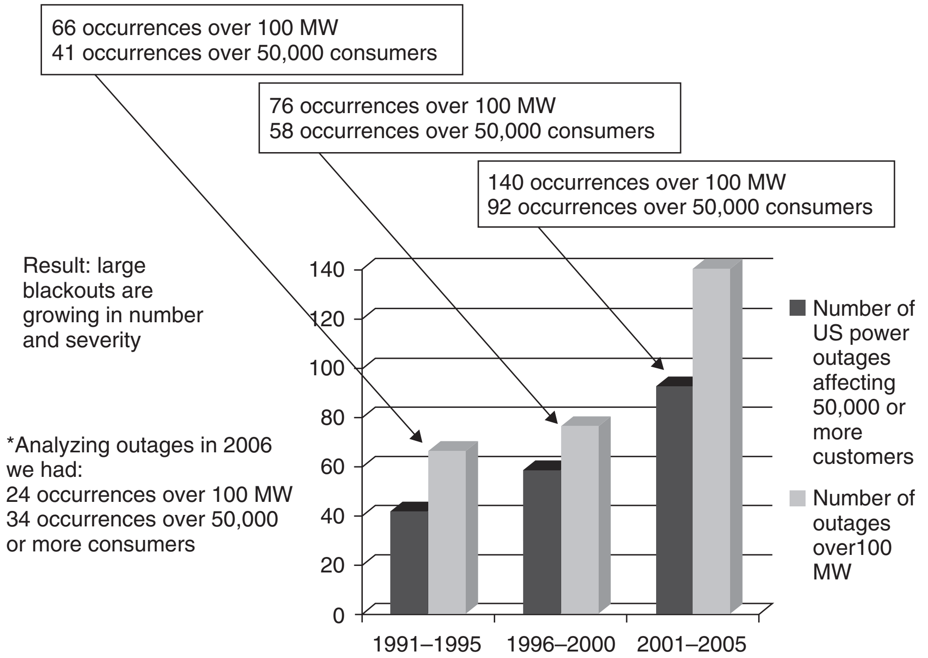

FIGURE 5.1 Historical analysis of outages 1991–2005 (please also note that annual increases in load, about 2% per year, and corresponding increase in consumers should also be taken into account). [Data courtesy of NERC's Disturbance Analysis Working Group database.]

of customers affected during 1991–2005. These data from the NERC's Disturbance Analysis Working Group (DAWG) are a subset of the total outages that are required to be reported to DOE's EIA. Going through the more comprehensive data sets from DOE's EIA, during 2001–2005 there were 162 outages of 100 MW or more, and 150 outages affecting >50,000 consumers.

In addition, analyzing outages in 2006 (NERC's data), in 1 year we had: 24 occurrences over 100 MW and 34 occurrences over 50,000 or more consumers.

At the core of the power infrastructure investment problem lie two paradoxes of restructuring, one technical and one economic. Technically, the fact that electricity supply and demand must be in instantaneous balance at all times must be resolved with the fact that new power infrastructure is extraordinarily complex, time-consuming, and expensive to construct. Economically, the theory of deregulation aims to achieve the lowest price through increased competition. However, the market reality of electricity deregulation has often resulted in a business-focused drive for maximum efficiency to achieve the highest profit from existing assets, and not resulted in lower prices or improved reliability. Both the technical and economic paradoxes could be resolved by knowledge and technology.

Whether or not the power industry renews its traditional levels of investment in research and in new transmission lines, or the government clarifies its regulatory role in the making and dispatching of electricity, the grid will have to go on functioning. Fortunately, several recent innovations promise to make better use of the existing electrical network.

Grid Challenges

Power produced in one place and used hundreds of miles away creates new opportunities, especially in terms of encouraging the construction of new power generation, possibly transmission, and in making full use of the power produced, rights of way and assets; but it also creates challenges:

1. *Regulatory Challenges.* More than ever power transmission is an interstate transaction. This has led to numerous conflicts between federal statutes applying to energy and rules set up by public utility commissions in the various states. Generally the federal goal is to maximize competition, even if this means that traditional utility companies should divest themselves of their own generators. Since the 1990s, the process of unbundling utility services has brought about a major change in the way that energy companies operate. On the other hand, the goal of state regulators has generally been to provide reliable service and the lowest possible prices for customers in state.
2. *Investment Challenge.* Long-distance interstate routing, or "wheeling," of power, much encouraged by the federal government, has put the existing transmission network, largely built in the 1970s and 1980s in a time of sovereign utilities, under great stress. Money spent by power companies on research is much lower than in past decades. Reserve power capacity, the amount of power-making to be used in emergencies, which was 25–30% 25 years ago is now at 10–15%.
3. *Security, Reliability, and Innovation Challenges.* The August 2003 Northeast blackout, when operators did not know of the perilous state of their grid and how a local power shutdown could propagate for hundreds of miles, leaving tens of millions in the dark, demonstrated the need for mandatory reliability rules governing the daily operation of the grid. Such rules are now coming into place.
4. *Marketplace Challenges.* Some parts of the power business operate now without regulations. Other parts, such as the distribution of power to customers might still be regulated in many states, but the current trend is toward removing rules. The hope here is that rival energy companies, competing for customers, will offer more services and keep their prices as low as possible. Unfortunately, in some markets, this has the risk of manipulating the market to create energy shortages, even to the extent of requiring rolling blackouts in an effort to push prices higher.

These are recognized by the power companies and stakeholders in a rapidly changing marketplace. The public, usually at times of dramatic blackouts, and the business community, which suffers losses of over $80 billion per year, have taken notice. Even the Congress, which must negotiate the political fallout of power problems and establish laws governing the industry, takes up the problems of power transmission and distribution on a recurring basis, although usually in the context of the larger debate over energy policy. In the meantime, the US power grid has to be administered and electricity has to be delivered to millions of customers. Fortunately, many new remedies, software and hardware, are at hand.

5.7 OPTIONS AND POSSIBLE FUTURES—WHAT WILL IT TAKE TO SUCCEED?

Revolutionary developments in both information technology and material science and engineering promise significant improvement in the security, reliability, efficiency, and cost-effectiveness of all critical infrastructures. Steps taken now can ensure that critical infrastructures continue to support population growth and economic growth without environmental harm.

As a result of increased demand, regulatory uncertainty, and the increasing connectedness of critical infrastructures, it is quite possible that in the near future the ability, for example, of the electricity grid to deliver the power that customers require in real time, on demand, within acceptable voltage and frequency limits, and in a reliable and economic manner may become severely tried. Other infrastructures may be similarly tested.

At the same time, deregulation and restructuring have added to the concern about the future of the electric power infrastructure (and other industries as well). This shift marked a fundamental change from an industry that was historically operated in a very conservative and largely centralized way as a regulated monopoly, to an industry operating in a decentralized way by economic incentives and market forces. The shift impacts every aspect of electrical power including its price, availability, and quality. For example, as a result of deregulation, the number of interacting entities on the electric grid (and hence its complexity) has been dramatically increasing while, at the same time, a trend toward reduced capacity margins has appeared. Yet when deregulation was initiated, little was known about its large-scale, long-term impacts on the electricity infrastructure, and no mathematical tools were available to explore possible changes and their ramifications.

It was in this environment of concern that the smart self-healing grid was conceived. One event in particular precipitated the creation of its foundations: a power outage that cascaded across the western United States and Canada on 10 August 10 1996. This outage began with two relatively minor transmission-line faults in Oregon. But ripple effects from these faults tripped generators at McNary dam, producing a 500 MW-wave of oscillations on the transmission grid that caused separation of the primary West Coast transmission circuit, the Pacific Intertie, at the California–Oregon border. The result: blackouts in 13 states and provinces costing some \$1.5 billion in damages and lost productivity. Subsequent analysis suggests that shedding (dropping) some 0.4% of the total load on the grid for just 30 min would have prevented the cascading effects and prevented large-scale regional outages (note that load-shedding is not typically a first option for power grid operators faced with problems).

From a broader perspective, any critical national infrastructure typically has many layers and decision-making units and is vulnerable to various types of disturbances. Effective, intelligent, distributed control is required that would enable parts of the constituent networks to remain operational and even automatically reconfigure in the event of local failures or threats of failure. In any situation subject to rapid changes, completely centralized control requires multiple, high data rate, two-way communication links, a powerful central computing facility, and an elaborate operations control center. But all of these are liable to disruption at the very time when they are most needed (i.e. when the system is stressed by natural disasters, purposeful attack, or unusually high demand).

Had the results of the CIN/SI been in place at the time of the August 2003 blackout, the events might have unfolded very differently. For example, fault anticipators located at one end of the high voltage transmission lines would have detected abnormal signals, and made adaptive reconfigurations of the system to sectionalize the disturbance and minimize impact component failures several hours before the line failed. The look-ahead simulations would have identified the line as having a higher than normal probability of failure. Quickly, cognitive agents (implemented as distributed software and hardware in the infrastructure components and in control centers) would have run failure scenarios on their virtual system models to determine the ideal corrective response. When the high voltage line actually failed, the sensor network would have detected the voltage fluctuation and communicated the information to reactive agents located at substations. The reactive agents would have executed the predetermined corrective actions, isolating the high voltage line and rerouting power to other parts of the grid. No customer in the wider area would even be aware that a catastrophic event had been impending, or have noticed the lights flickering.

Such an approach provides an expanded stability region with larger operational range. As the operating point nears the limit to how much the grid could have adapted (e.g. by automatically rerouting power and/or balancing by dropping a small amount of load or generation), rather than cascading failures and large-scale regional system blackouts, the system would be reconfigured to minimize severity or size of outages to shorten duration of brownouts or blackouts, and to enable rapid and efficient restoration.

This kind of distributed grid control has many advantages if coordination, communication, bandwidth, and security can be assured. This is especially true when the major components are geographically dispersed, as in a large telecommunications, transportation, or computer networks. It is almost always preferable to delegate as much of the control as is practical, to the local level.

The simplest kind of distributed control would combine remote sensors and actuators to form regulators (e.g. intelligent electronically controlled secure devices), and adjust their set points or biases with signals from a central location. Such an approach requires a different way of modeling—of thinking about, organizing and designing—the control of a complex, distributed system. Recent research results from a variety of fields, including nonlinear dynamical systems, artificial intelligence, game theory, and software engineering have led to a general theory of complex adaptive systems (CAS). Mathematical and computational techniques originally developed and enhanced for the scientific study of CAS provide new tools for the engineering design of distributed control so that both, centralized decision-making and the communication burden it creates, can be minimized. The basic approach to analyzing a CAS is to model its components as independent adaptive software and hardware "agents"—partly cooperating and partly competing with each other in their local operations while pursuing global goals set by a minimal supervisory function.

If organized in coordination with the internal structure existing in a complex infrastructure and with the physics specific to the components they control, these agents promise to provide effective local oversight and control without need of excessive communications, supervision, or initial programming. Indeed, they can be used even if human understanding of the complex system in question is incomplete. These agents exist in every local subsystem—from "horseshoe nail" up to "kingdom"—and perform preprogrammed self-healing actions that require an immediate response. Such simple agents are already embedded in many systems today, such as circuit breakers and fuses as well as diagnostic routines. The observation is that we can definitely account for loose nails and save the kingdom.

Another key insight came out of analysis of forest fires, by researchers at CalTech and UC-Santa Barbara, in the one of the six funded consortia, which I led during 1998–2002.

They found forest fires to have “failure-cascade” behavior, similar to electric power grids. In a forest fire the spread of a spark into a conflagration depends on how close together the trees are. If there is just one tree in a barren field and it is hit by lightning, it burns but no big blaze results. But if there are many trees and they are close enough together—which is the usual case with trees because Nature is prolific and efficient in using resources—the single lightning strike can result in a forest fire that burns until it reaches a natural barrier such as a rocky ridge, river, or road. If the barrier is narrow enough for a burning tree to fall across it, or it includes an inflammable flaw such as a wooden bridge, the fire jumps the barrier and burns on. It is the role of first-response wild-land fire fighters such as smoke jumpers, to contain a small fire before it spreads by reinforcing an existing barrier or scraping out a defensible fire line barrier around the original blaze.

Similar results hold for failures in electric power grids. For power grids, the “one-tree” situation is a case in which every single electric socket had a dedicated wire connecting it to a dedicated generator. A lightning strike on any wire would take out that one circuit and no more. But like trees in Nature, electrical systems are designed for efficient use of resources, which means numerous sockets served by a single circuit and multiple circuits for each generator. A failure anywhere on the system causes additional failures until a barrier—such as a surge protector or circuit breaker—is reached. If the barrier does not function properly or is insufficiently large, the failure bypasses it and continues cascading across the system.

These preliminary findings suggest approaches by which the natural barriers in power grids may be made more robust by simple design changes in the configuration of the system, and eventually show how small failures might be contained by active smoke-jumper-like controllers before they grow into large problems. Other research into fundamental theory of complex interactive systems explored means of quickly identifying weak links and failures within a system.

CIN/SI developed, among other things, a new vision for the integrated sensing, communications, and control of the power grid. Some of the pertinent issues are why or how to develop controllers for centralized versus decentralized control and issues involving adaptive operation and robustness to disturbances that include various types of failures.

Modern computer and communications technologies now allow us to think beyond the protection systems and the central control systems to a fully distributed system that places intelligent devices at each component, substation and power plant. This distributed system will enable us to build a truly smart grid.

One of the problems common to the management of central control facilities is the fact that any equipment changes to a substation or power plant must be described and entered manually into the central computer system’s database and electrical one-line diagrams. Often this work is done some time after the equipment is installed and there is thus a permanent set of incorrect data and diagrams in use by the operators. What is needed is the ability to have this information entered automatically when the component is connected to the substation—much as a computer operating system automatically updates itself when a new disk drive or other device is connected.

5.8 THE ROAD AHEAD

A new mega-infrastructure is emerging from the convergence of energy (including the electric grid, water, oil and gas pipelines), telecommunications, transportation, Internet and electronic commerce. Furthermore, in the electric power industry and other critical infrastructures, new ways are being sought to improve network efficiency and eliminate congestion problems without seriously diminishing reliability and security.

Electric power systems constitute the fundamental infrastructure of modern society. Often continental in scale, electric power grids and distribution networks reach virtually every home, office, factory, and institution in developed countries and have made remarkable, if remarkably insufficient, penetration in developing countries such as China and India.

The electric power grid can be defined as the entire apparatus of wires and machines that connects the sources of electricity and the power plants, with customers and their myriad needs. Once "loosely" interconnected networks of largely local systems, electric power grids now increasingly host large-scale, long-distance wheeling of power from one region to another. Likewise, the connection of distributed resources—at the moment, primarily small generators—are growing rapidly. The extent of interconnectedness, like the number of sources, controls, and loads, has grown with time. In terms of the sheer number of nodes, as well as the variety of sources, controls, and loads, electric power grids are among the most complex networks made.

Global trends toward interconnectedness, privatization, deregulation, economic development, accessibility of information, and the continued technical trend of rapidly advancing information and telecommunication technologies all suggest that the complexity, interactivity, and interdependence of infrastructure networks will continue to grow.

The existing electricity infrastructure evolved to its technology composition today from the convolution of several major forces, only one of which was technologically based. During the past 10 years, we have systematically scanned science and technology, investment, and policy dimensions to gain clearer insight on current science and technology assets when looked at from a consumer-centered future perspective, rather than just incremental contributions to today's electric energy system and services.

The goal of transforming the current infrastructures to self-healing energy-delivery, and computer and communications networks with the unprecedented robustness, reliability, efficiency and quality for customers and our society is ambitious. This will require addressing challenges and developing tools, techniques, and integrated probabilistic risk assessment/impact analysis for wide-area sensing and control for digital-quality infrastructure such as sensors, communication and data management, as well as improved state estimation, monitoring and simulation linked to intelligent and robust controllers leading to improved protection and discrete-event control. These follow-on activities will build on the foundations of CIN/SI and current programs that include self-healing systems and real-time dynamic information and emergency management and control.

More specifically, the operation of a modern power system depends on a complex system of sensors and automated and manual controls, all of which are tied together through communication systems. While the direct physical destruction of generators, substations, or power lines, may be the most obvious strategy for causing blackouts, activities that compromise the operation of sensors, communication and control systems by spoofing, jamming, or sending improper commands could also disrupt the system, cause blackouts, and in some cases result in physical damage to key system components. Hacking and cyber attacks are becoming increasingly common.

Most early communication and control systems used in the operation of the power system were carefully isolated from the outside world, and were separate from other systems such as corporate enterprise computing. However, economic pressures created incentives for utilities to make greater use of commercially available communications and other equipment that was not originally designed with security in mind. Unfortunately from a security perspective, such interconnections with office and electronic business systems through other layers of communications created vulnerabilities. While this problem is now well understood in the industry and corrective action is being taken, we are still in a transition period during which some control systems have been inadvertently exposed to access from the Internet, intranets, and remote dial-up capabilities that are vulnerable to cyber intrusions.

Many elements of the distributed control systems now in use in power systems are also used in a variety of applications in process control, manufacturing, chemical process controls and refineries, transportation, and other critical infrastructure sectors and hence are vulnerable to similar modes of attack. Dozens of communication and cyber security intrusions, and penetration red-team "attacks" have been conducted by DOE, EPRI, electric utilities, commercial security consultants, KEMA, and others. These "attacks" have uncovered a variety of cyber vulnerabilities including unauthorized access, penetration and hijacking of control.

While some of the operations of the system are automatic, ultimately human operators in the system control center make decisions and take actions to control the operation of the system. In addition, to the physical threats to such centers and the communication links that flow in and out of them, one must also be concerned about two other factors: the reliability of the operators within the center, and the possibility that insecure code has been added to one of the programs in a central computer. The threats posed by "insider" threats, as well as the risk of a "Trojan horse" embedded in the software of one or more of the control centers is real, and can only be addressed by careful security measures both, within the commercial firms that develop and supply this software, and careful security screening of the utility and outside service personnel who perform software maintenance within the center. Today security patches are often not always supplied to end users, or users are not applying the patches for fear of impacting system performance. Current practice is to apply the upgrades or patches after SCADA vendors thoroughly test and validate patches, sometimes incurring a delay of several months in patch deployment.

As an example related to numerous major outages, narrowly programmed protection devices have contributed to worsening the severity and impact of the outage—typically performing a simple on/off logic which locally acts as preprogramme while destabilizing a larger regional interconnection. With its millions of relays, controls and other components, the parameter settings and structures of the protection devices and controllers in the electricity infrastructure can be a crucial issue. It is analogous to the poem "For want of a horseshoe nail ... the kingdom was lost" that is, relying on an "inexpensive 25 cent chip" and narrow control logic to operate and protect a multibillion dollar machine.

As a part of enabling a smart self-healing grid, we have developed fast look-ahead modeling and simulation, precursor detection, adaptive protection, and coordination methods that minimize impact on the whole system performance (load dropped as well as robust rapid restoration). There is a need to coordinate the protection actions of such relays and controllers with each other to achieve overall stability. A single controller or relay cannot do all, and they are often tuned for worst cases, therefore control action may become excessive from a system-wide perspective. On the other hand, they may be tuned for the best case, and then the control action may not be adequate. This calls for coordinating protection and control—neither agent, using its local signal, can by itself stabilize a system; but with coordination, multiple agents, each using its local signal, the overall system can be stabilized.

It is important to note that the key elements and principles of operation for interconnected power systems were established in the 1960s prior to the emergence of extensive computer and communication networks. Computation is now heavily used in all levels of the power network for planning and optimization, fast local control of equipment, and processing of field data. But coordination across the network happens on a slower time-scale. Some coordination occurs under computer control, but much of it is still based on telephone calls between system operators at the utility control centers, even (or especially!) during emergencies.

Systems should be motivated by living beings' resilience and robustness to operate to some degree after injury, by developing compensatory behaviors and to autonomously recover from unexpected damage through continuous self-modeling, thus providing increased "situational awareness," and ability to be "damage adaptive," to withstand and possibly recover from "injury," attacks, or unexpected damage.

Grid "self-modeling" could survive emergencies and adapt to new conditions quicker than grids that are not "self-conscious." Enabled by distributed sensing and measurement and combined with Fast Modeling and Simulation we have developed and pilot tested data-driven control and operation of regional power grids, analogous to the continuous self-modeling and compensation of damaged fighter planes and intelligent robots in the face of unexpected damage.

From a broader perspective, any critical national infrastructure typically has many layers and decision-making units and is vulnerable to various types of disturbances. Effective, intelligent, distributed control is required that would enable parts of the constituent networks to remain operational and even automatically reconfigure in the event of local failures or threats of failure. In any situation subject to rapid changes, completely centralized control requires multiple, high data rate, two-way communication links, a powerful central computing facility, and an elaborate operations control center. But all of these are liable to disruption at the very time when they are most needed (i.e. when the system is stressed by natural disasters, purposeful attack, or unusually high demand).

When failures occur at various locations in such a network, the whole system breaks into isolated "islands," each of which must then fend for itself. With the intelligence distributed, and the components acting as independent agents, those in each island have the ability to reorganize themselves and make efficient use of whatever local resources remain to them, in ways consonant with the established global goals to minimize adverse impact on the overall network. Local controllers will guide the isolated areas to operate independently while preparing them to rejoin the network, without creating unacceptable local conditions either during or after the transition. A network of local controllers can act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limiting their messages to only that information necessary to achieve global optimization and facilitate recovery after failure.

Over the last 12 years, our efforts in this area have developed, among other things, a new vision for the integrated sensing, communications, protection and control of the power grid. Some of the pertinent issues are why or how to develop protection and control devices for centralized versus decentralized control, and issues involving adaptive operation and robustness to various destabilizers. However, instead of performing *in vivo* societal tests which can be disruptive, we have performed extensive "wind-tunnel" simulation testing (in Silico) of devices and policies in the context of the whole system along with prediction of unintended consequences of designs and policies to provide a greater understanding of how policies, economic designs and technology might fit into the continental grid, as well as guide in their effective deployment and operation.

Advanced technology now under development or under consideration, holds the promise of meeting the electricity needs of a robust digital economy. The architecture for this new technology framework is evolving through early research on concepts and the necessary enabling platforms. This architectural framework envisions an integrated, self-healing, electronically controlled electricity supply system of extreme resiliency and responsiveness—one that is fully capable of responding in real time to the billions of decisions made by consumers and their increasingly sophisticated agents. The potential exists to create an electricity system that provides the same efficiency, precision, and interconnectivity as the billions of microprocessors that it will power.

5.9 COST AND BENEFIT

Electricity shall prevail at the quality, efficiency and reliability that customers demand and are willing to pay for. On the one hand the question is who provides it; on the other hand it is important to note that achieving the grid performance, security and reliability are a national profitable investment, not a cost burden on the taxpayer. The economic payback is three to seven times and in some cases an order of magnitude greater than the money invested. Further, the payback starts with the completion of each sequence of grid improvement. The issue is not merely who invests money because that is ultimately the public, whether through taxes or kilowatt hour rates. Considering the impact of regulatory agencies, they should be able to induce the electricity producers to plan and fund the process. That may be the most efficient way to get it in operation. The current absence of a coordinated national decision-making is a major obstacle. State’s rights and State PUC regulations have removed the individual State’s utility motivation for a national plan. Investor utilities face either collaboration on a national level, or a forced nationalization of the industry.

Simply replicating the existing system through expansion or replacement will not only be technically inadequate to meet the changing demands for power, but will produce a significantly higher price tag. Through the transformative technologies outlined here, the nation can put in place a twenty-first century power system capable of eliminating critical vulnerabilities while meeting intensified consumer demands, and in the process, save society considerable expense.

What is at stake is whether our national critical infrastructures and the underpinning interconnected networks will continue to function reliably and securely or not. This program will produce significant advances in the security, robustness, efficiency, and performance of the power grid and its interdependent infrastructures. The tools indicated will provide unprecedented stability, reliability, efficiency, and service quality. A major outage (affecting 7 million or more customers) occurs about once every decade costing over $2 billion—smaller disturbances are commonplace with very high cost to the customers and our society. On a given day, there are 500,000 customers without power for 2 h or more in the United States. The above programs cost about $170–200 million per year for R&D, and up to about $400 million per year over a decade for fielding, testing and integration into the system. Therefore we can save about five to sevenfold in prevention and mitigation of disturbances. Other benefits include the following:

- builds a smart generation and delivery infrastructure, an "electrinet," with in-built security;
- creates opportunities for a risk-managed integration of diverse risk-managed balanced portfolios of generation sources;
- improves security and observability of system operation and control;
- refines definition of system operating limits'
- serves transmission system market demands;
- minimizes transmission costs;
- reduces utage cost;
- improves system simulation models;
- improves management of system reliability and asset integration (from distributed generators and renewables, to central power plants).

As expressed in the July 2001 issue of *Wired* magazine: "The best minds in electricity R&D have a plan: Every node in the power network of the future will be awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, humming—and interconnected with everything else." The technologies included, for example the concept of self-healing electricity infrastructure, methodologies for fast look-ahead simulation and modeling, adaptive intelligent islanding and strategic power infrastructure protection systems, are of special interest for improving grid security from terrorist attack.

5.10 NEXT STEPS

How to control a heterogeneous, widely dispersed, yet globally interconnected system is a serious technological problem in any case. It is even more complex and difficult to control it for optimal efficiency and maximum benefit to the ultimate consumers while still allowing all its business components to compete fairly and freely. A similar need exists for other infrastructures, where future advanced systems are predicated on the near-perfect functioning of today's electricity, communications, transportation, and financial services.

From a national perspective, a key grand challenge before us is how do we redesign, retrofit, and upgrade the nearly 220,000 miles of electromechanically controlled system into a smart self-healing grid that is driven by a well-designed market approach.

Creating a smart grid with self-healing capabilities is no longer a distant dream; we have made considerable progress. But considerable technical challenges as well as several economic and policy issues remain to be addressed.

Funding and sustaining innovations, such as the self-healing grid, remain a challenge as utilities must meet many competing demands on precious resources while trying to be responsive to their stakeholders, who tend to limit R&D investments to immediate applications and short-term ROI. In addition, utilities have little incentive to invest in the longer term. For regulated investor–owned utilities there is added pressure caused by Wall Street to increase dividends.

Several reports and studies have estimated that for existing technologies to evolve and for the innovative technologies to be realized, a sustained annual research and development investment of $10 billion is required. However, the current level of R&D funding in the electric industry is at an all-time low. The investment rates for the electricity sector are the lowest rates of any major industrial sector with the exception of the pulp and paper industry. The electricity sector invests at most, only a few tenths of a percent of sales in research. This is in contrast to fields such as electronics and pharmaceuticals in which R&D investment rates have been running between 8 and 12% of net sales; all of these industry sectors fundamentally depend on reliable electricity.

A balanced, cost-effective approach to investments and use of technology can make a sizable difference in mitigating the risk. Electricity shall prevail at the quality, efficiency, and reliability that customers demand and are willing to pay for. On the one hand, the question is, "Who provides it?" on the other hand, it is important to note that achieving the grid performance, security, and reliability are a profitable national investment, not a cost burden on the taxpayer. The economic payback is three to seven times greater than the money invested. Further, the payback starts with the completion of each sequence of grid improvement. The issue is not merely who invests money, because that is ultimately the public, but whether it is invested through taxes or kWh rates. Considering the impact of regulatory agencies, they should be capable of inducing the electricity producers to plan and fund the process; this may be the most efficient way to get it in operation. The current absence of a coordinated national decision-making body is a major obstacle. State's rights and State PUC regulators have removed the individual State's utility motivation for a national plan. Investor utilities face either collaboration on a national level or a forced nationalization of the industry.

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REFERENCES

1. Amin, S. M. (2003). North America's electricity infrastructure: are we ready for more perfect storms? *IEEE Secur. Priv. Mag.* **1**(5), 19–25.

FURTHER READING

Amin, S. M. (2008). For the good of the grid: toward increased efficiencies and integration of renewable resources for future electric power networks. *IEEE Power Energy Mag.* **6**(6), 48–59.

Amin, S. M., and Stringer, J. (2008). The electric power grid: today and tomorrow. *MRS Bull.* **33**(4), 399–407.

Amin, S. M., and Schewe, P. F. (2007). *Preventing Blackouts*. Scientific American, pp. 60–67.

Schewe, P. F. (2007). *The Grid: A Journey Through the Heart of our Electrified World*. Joseph Henry Press.

Amin, S. M. (2005). Scanning the technology: energy infrastructure defense systems. *Spec. Issue Proc. IEEE* **93**(5), 857–871.

Amin, S. M., and Gellings, C. (2006). The North American power delivery system: balancing market restructuring and environmental economics with infrastructure security. *Energy* **31**(6–7), 967–999.

Amin, S. M., Carlson, L. W., and Gellings, C. (2006). *Galvin Electricity Initiative: Technology Scanning, Mapping and Foresight*. Galvin Electricity Project, Inc., EPRI, Palo Alto, CA, Chicago, IL, p. 70.

Amin, S. M., and Wollenberg, B. F. (2005). Toward a smart grid: power delivery for the 21st century. *IEEE Power Energy Mag.* **3**(5), 34–41.

Amin, S. M. (2005). Energy infrastructure defense systems. *Proc. IEEE* **93** (5).

Amin, S. M. (2005). Powering the 21st century: we can—and must—modernize the grid. *IEEE Power Energy Mag.*, 93–96.

Amin, S. M. (2004). Electricity. In *Digital Infrastructures: Enabling Civil and Environmental Systems through Information Technology*, R. Zimmerman, and T. Horan, Eds. pp. 116–140, Chapter 7.

EPRI. (2003). *Complex Interactive Networks/Systems Initiative: Final Summary Report—Overview and Summary Final Report for Joint EPRI and US DoD University Research Initiative*. EPRI, Palo Alto, CA, p. 155.

Amin, S. M. (2001). Special issues of IEEE control systems magazine on control of complex networks. **21** (6), (2002). 22(1).

Amin, S. M. (2001). Toward self-healing energy infrastructure systems. cover feature in the *IEEE Comput. Appl. Power* **14**(1), 20–28.

Amin, S. M. (2000). Toward self-healing infrastructure systems. cover feature in the *IEEE Comput. Mag.* **33**(8), 44–53.

Amin, S. M. (2000). National infrastructures as complex interactive networks. In *Automation, Control, and Complexity: An Integrated Approach*, T. Samad, and J. Weyrauch, Eds. John Wiley and Sons, New York, pp. 263–286, chapter 14.

6

NANO-ENABLED POWER SOURCE

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6.1 SCIENTIFIC OVERVIEW

As with portable consumer electronics, there is an insatiable demand for more power in most military applications. The exponential growth in integrated circuit performance over the past 30 years, as predicted by the Moore's law, accelerated the demand for power in many consumer electronics and military devices. Unfortunately, the pace of development of electrochemical cells or other power sources cannot keep up with the exponential growth of the integrated circuit and has become a limiting technology for electronic microdevices such as miniaturized communication devices (Fig. 6.1). Although the number of transistors per integrated circuit has been doubled every couple of years since 1970, the performance gain per year for commercial cells is usually a small percentage, depending on the cell chemistry. Battery technology performance has increased about 2% per year. The newer lithium-ion (Li-ion) rechargeable chemistry performance gain in terms of capacity has been about 12% per year since the introduction in 1991, but still has not kept pace with demand. Thus, the accelerating growth in the digital devices has often been limited by the incremental improvement in battery performance.

Nanotechnology offers an opportunity for improvement in power and energy density of power sources [1]. Generally speaking, nanotechnology can be classified either as nanoscale fabrication technology of devices or the revolutionary enhancement of performance by using nanoscale materials. Nanomaterials are usually defined dimensionally, with features such as particle dimension or porosity in the range of 1–100 nm. Fabrication technology for nanodevices is based on the so-called "bottom-up" approach whereby complex structures are self-assembled from the atomic or molecular level, as is found in all biological systems. Progress in this area has been slow due to inadequate control at the atomic level with currently available equipment. On the other hand, much progress has been made in developing nanomaterials as evidenced by commercially available carbon nanotubes from many sources (recent search found >25 websites that claim to be

Energy Systems Security, Edited by John G. Voeller

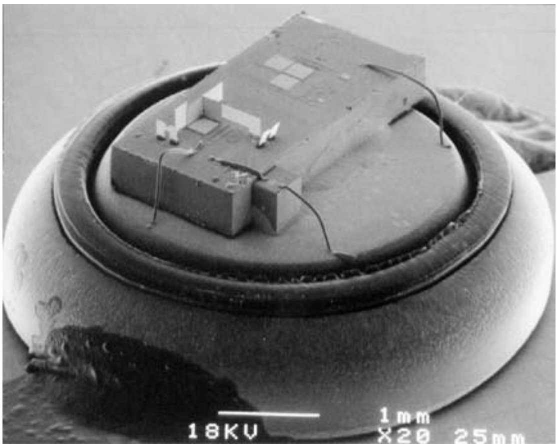

FIGURE 6.1 Photograph of a sensor "mote" (only 2 mm × 4 mm) containing a sensor, microprocessor, and communications electronics mounted on top of a much larger coin cell (from www-bsac.eecs.berkeley.edu). The operation of this device is limited by the lifetime of the battery.

"dedicated to nanotubes"). Nanomaterials hold the potential to be an enabling technology for energy storage and conversion devices by increasing energy storage capacity, discharge rate capability, or stability over the lifetime of the device. Thus, the focus of this chapter is to review nano-enabled power sources based on judicious implementation of nanostructured materials.

6.1.1 High Power Cells

Increasing power and rate capability of batteries are the important applications of nanoscale materials. By reducing the particle size of the active materials from submicron to nanoscale, one should be able to increase diffusion rates in these solids by two orders of magnitude and improve the power capability. Typical battery active materials are on the order of 10 μm (10,000 nm). Because of the diffusion distance required, full charge and discharge usually require a period of 30 min to 1 h to diffuse through 10,000 nm. According to the diffusion equation, the diffusion time, t, is proportional to r^2/D, where r is the diffusion length and D is the diffusion coefficient. It is difficult to decrease drastically the intrinsic diffusion coefficient, but one can shorten the diffusion length by 2–3 orders of magnitude through the use of nanomaterials, and achieve minutes or subminutes charge or discharge rates. One such example is the nano-lithium titanate (nano-$Li_4Ti_5O_{12}$) of approximately 30 nm. Nano-$Li_4Ti_5O_{12}$ was demonstrated to have greater than 80% utilization at 10 C (6 min) continuous discharge rate while 1 μm macro-$Li_4Ti_5O_{12}$ had only about 10% utilization at the same discharge rate [2] (Fig. 6.2). As anode, nano-$Li_4Ti_5O_{12}$ enabled fast charge Li-ion cells was demonstrated in Toshiba's 1-min charge Li-ion cells [3].

Another example of a nano-enabling material is the olivine lithium iron phosphate, $LiFePO_4$. The low electronic conductivity of $LiFePO_4$ results in very poor rate performance. However, when $LiFePO_4$ is reduced to the nanodomain and coated with nanocarbon particles, the conductivity and power density were improved up to seven and one orders of magnitude, respectively [4]. High power Li-ion cells based on modified

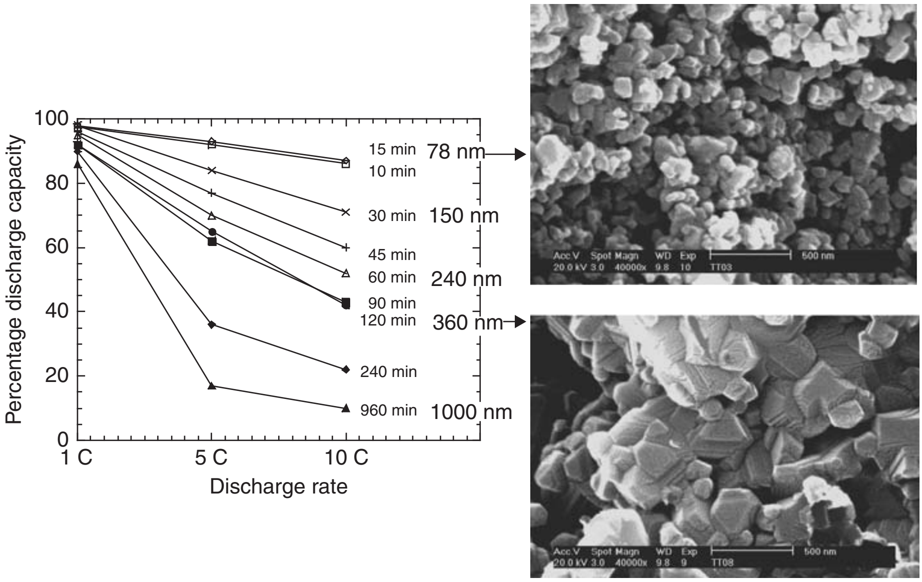

FIGURE 6.2 Nano- versus macro-$Li_4Ti_5O_{12}$ capacity utilization under high discharge rates [2].

nano-$LiFePO_4$ are being commercialized by A123Systems. These cells were claimed to be capable of delivering about one order of magnitude more power (>3000 W/kg) than conventional Li-ion cells [5], similar to that of a supercapacitor but with the energy density of that of a rechargeable battery, albeit lower energy density than conventional Li-ion cells.

Similarly, by reducing the particle size to nanoscale, one can also enhance the high power performance of electrochemical capacitors. In an electrochemical capacitor, charge is stored on the surface of a porous, high-surface-area electrode, and not in the bulk of the material. Very high surface area leads to high power delivery, and capacitances of ~100 F/g have been measured with carbon foams. Because there is no movement of mass within the electrode material and therefore no change in volume in the anode or cathode during charge and discharge, the cycle life of these systems is essentially infinite with a very poor specific energy, typically less than 1 Wh/kg. However, using asymmetric hybrid configuration, containing one battery electrode and one electrochemical double-layer capacitor electrode, Amatucci et al. have demonstrated energy density greater than 20 Wh/kg at a power density of 3000 W/kg [6]. The asymmetric capacitor was enabled by the nano-$Li_4Ti_5O_{12}$, which not only enabled high power but also high cycle life. Cycle life greater than 1 million cycle was demonstrated using the nano-$Li_4Ti_5O_{12}$ (Fig. 6.3), which has unique zero volume change during cycling. Thus, the asymmetric capacitors serve to bridge the performance gap between batteries (high energy but low power) and capacitor (high power but low energy).

Nanotech-enabled optimization should also lead to new high power-density electrochemical capacitors as a consequence of the recent determination of the true nature of pseudocapacitance in hydrous ruthenium oxide (designated as $RuO_2{\cdot}xH_2O$). For $x=0.5$, 720 F/g can be stored in hydrous ruthenium oxide [7], 5-10 times greater than that stored at high-surface-area carbon supercapacitors. This form of the material appears amorphous to X rays, but upon medium-range structural analysis was shown to form a

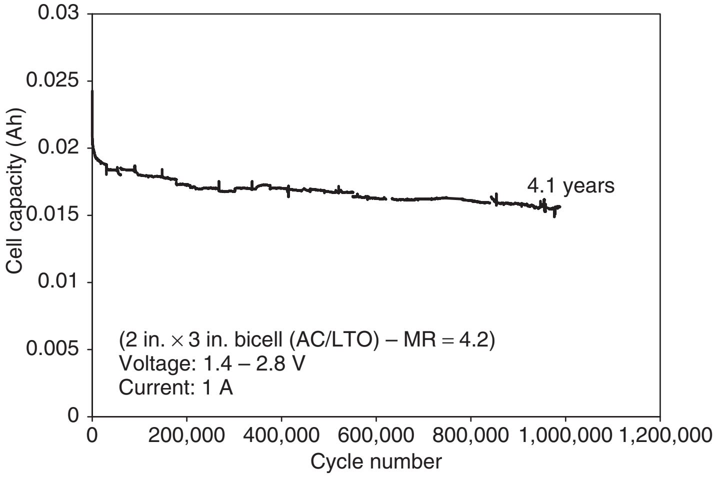

FIGURE 6.3 Cycle life of nano-$Li_4Ti_5O_{12}$ versus carbon asymmetric electrochemical capacitor [courtesy of Prof. Amatucci of Rutgers University].

nanocomposite of metallic, anhydrous rutile-like RuO_2 nanocrystallites whose surfaces contain of proton-conductive structural water associated with Ru–O [8]. The competing percolation networks of electronic and protonic conduction pathways provide the optimized multifunctionality of hydrous ruthenium oxide for energy storage. This new structural understanding on the nanoscale can also serve as a new archetype for the design of charge-storage materials.

6.1.2 High Capacity Cells

Nanomaterials open new options in preparing high capacity electrode materials. Today's high energy batteries rely almost exclusively on lithium or lithiated compounds since lithium is the lightest metal in the periodic table, has a high oxidation potential, large electrochemical equivalence, and good conductance. The energy density of lithium cells, and especially the state of the art (SOA) of Li-ion cells is limited by the energy density of the positive materials. The current SOA positive materials utilized intercalation reactions, which are limited to the amount of lithium transferred, thereby limiting electron transfer to typically less than 1e–per compound such as $LiMeO_2$, where Me is a transition metal.

$$1e^- + 1Li^+ + Me^{4+}O_2 \leftrightarrow LiMe^{3+}O_2$$

An alternative to the intercalation mechanism is to utilize the concept of reversible conversion compounds where multiple electrons can be transferred to the active electrode material to reduce it fully to the metal state and later reoxidize it back to the original compound.

$$3e^- + 3Li^+ + Me^{3+}X_3 \leftrightarrow 3LiF + Me^o$$

In theory, these reactions can lead to a specific energy greater than 1500 Wh/kg, or in a practical cell about 3*x* that of the SOA Li-ion cells based on $LiCoO_2$ positive electrode. Such reactions have been shown to exist for dichalcogenides and nitrides in the reaction range of 0.5–1.5 V [9]. To increase the potential of such reactions by at least 1 V, highly ionic halides are preferred over oxides, which are used in almost all lithium cells. Of the halides, the metal fluorides are most attractive due to their light weight and low solubility in nonaqueous electrolyte solvents relative to the heavier halides such as Cl and Br.

The theoretical attractiveness of metal fluorides as electrodes for primary cells has been known for over four decades. However, metal fluoride electrodes have not often been realized in part due to the fact that metal fluorides are very high bandgap materials resulting in electronic insulator characteristics. Amatucci et al. at Rutgers ESRG have demonstrated the enablement of a variety of high bandgap, insulating metal fluorides as reversible conversion electrodes through the use of nanocomposite technology [10]. By fabricating the desired metal fluoride materials as 20 nm crystallites in a small amount of conducting matrix, the electrochemical activity of these materials has been enabled. The reduction to nanocrystallite size (reducing electron path length by three orders of magnitude) has a threefold effect: developing a large volume of interface that is defect rich, creating surface states that assist both electron and ion diffusion, and enabling a larger portion of the material to be activated via electron tunneling reactions. A number of systems have been enabled, exhibiting near theoretical conversion voltages (2–3.2 V) and specific capacities from 400 to 700 mAh/g. Systems including fluorides and in some cases oxyfluorides of Fe, Ni, Co, Cr, Bi, and Cu have been enabled. Of these, CuF_2 has been identified as promising electrode material for primary cells, and FeF_3 and BiF_3 as promising electrode materials for rechargeable cells (Fig. 6.4) [11].

Nanotechnology also plays a key role in improving the effectiveness of the negative materials used in lithium cells. Firstly, in addition to aforementioned enhanced power performance, smaller particle sizes mean less internal stress on the electrodes during intercalation/deintercalation (the binder is more compressible and can more effectively tolerate the volume change), which could lead to increased cycle life. Secondly, smoother electrodes may also allow one to use thinner separators and/or electrolyte—again improving battery performance. Finally, one can replace carbon with a material that reversibly binds more than a single lithium atom per six host atoms (for example, Sn or Si). Nanosize composite anodes (e.g. carbon/silicon) offer the potential to take advantage of much

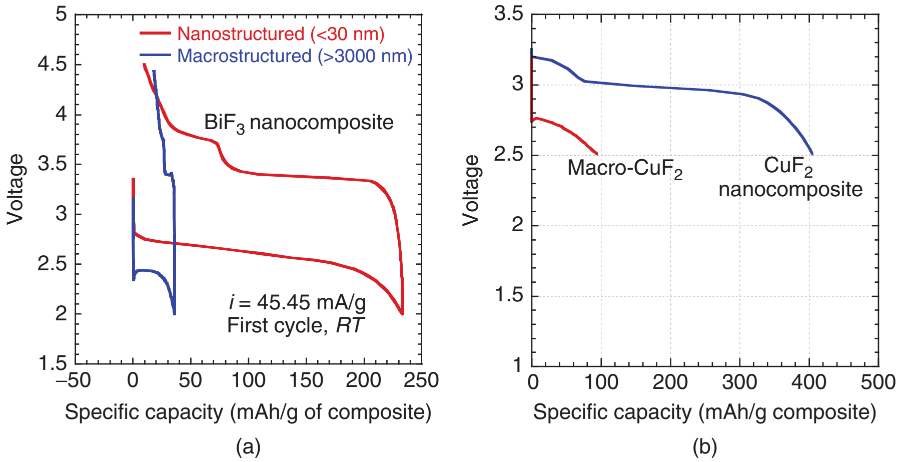

FIGURE 6.4 Theoretical capacity utilization enabled in (a) nano-BiF_3 and (b) nano-CuF_2.

higher capacity anode materials (e.g. $Li_4.Si$ has 10 times the capacity of LiC_6) and the smaller particle size can accommodate stresses that would fracture larger particles. This gives both higher capacity and reasonable stability on cycling [12]. The 40 wt% Si composite, which was the most silicon-rich composite that was tested, had a maximum reversible capacity of 1345 mAh/g and it still delivered 745 mAh/g, more than twice the capacity of LiC_6 in the 20th cycle.

SONY announced “Nexelion” cell in 2005 with carbon/Sn alloy anode [13], which increased the capacity per volume by 30%. In February 2007, Panasonic announced a further 40% increase in capacity by using alloy anode [14] and, although we do not know the composition, nanomaterials are suspected because they can accommodate the strain produced by the >300% volumetric expansion that accompanies conversion to Li alloy (e.g. conversion of Si to the lithiated compounds $Li_{22}Si_5$ has a 325% expansion). These advances in materials enable the production of high energy cells and batteries—Panasonic claims to have reached 740 Wh/l at the cell level.

6.2 GLOBAL EFFORT ON NANO-ENABLED POWER SOURCE TECHNOLOGIES

Ongoing research programs in the government (e.g. National Nanotechnology Initiative) and commercial sector are likely to benefit energy conversion technology. Fuel cells are of worldwide commercial interest, and DARPA has existing programs in thermoelectric materials development. The Department of Homeland Security should analyze and exploit these developments if nanotech-related breakthroughs appear that are relevant to their special needs.

Outside the United States, the most publicized R&D effort on nanotechnologies for power sources is the European consortium, Alistore [15]. Launched in 2004, the main objective of Alistore is to develop high power and high energy lithium cells based on nanomaterials. The consortium consisted of 16 European university research groups and University of Picardie at Amiens, France, was the program administrator. Other European companies are also very active in developing nanomaterials for fuel cells and energy harvesting technologies such as photovoltaic cells and thermoelectric energy harvester.

Government-sponsored nanotechnology efforts for power sources are not as well publicized among the Asian countries. However, there is already a strong effort by Japanese companies to commercialize nanomaterials such as carbon nanotubes for energy-related applications [16]. On the basis of the open literatures, we anticipated that other Asian countries such as Japan, China, and South Korea will become major players in nano-enabling materials for power sources within the next few years. NEDO in Japan has committed 2B ¥ for developing carbon nanotubes for high performance capacitors.

6.3 CRITICAL NEEDS ANALYSIS

Improved energy storage technology will benefit homeland security by providing increased performance across a wide range of portable electronic, including sensors, transmitters, and communication devices. Nanotechnology has strong potential to enable the development of batteries, capacitors, and hybrid systems with enhanced power and/or energy performance, which will enable the fabrication of micropower sources. In addition to the high power and high energy cells that were discussed above, technical areas that could be impacted by improvements in nanomaterials are other types of battery materials (e.g. electrolytes and separators) and fuel cells. The advent of micromachining and now nanomachining technology, combined with new and improved materials, provides opportunities for improving the performance of energy harvesting schemes.

6.3.1 3D Battery Architecture and Novel Fabrication Methods

Micropower sources capable of providing reliable rechargeable power under extreme conditions are critical to the development of security applications such as small autonomous distributed sensors. However, as Figure 6.5 illustrates, the energy density of the batteries decreases almost linearly as the size of the batteries decreases due to decreasing packaging efficiency. In addition, as batteries are reduced to the microscale, it becomes impractical (and almost impossible) to assemble cell stacks via the conventional layer-by-layer stacking approach. Extreme alignment precision is required in order to avoid any shorting between the microelectrodes. This necessitates the use of microelectronic fabrication techniques such as vacuum deposition. To date, the most mature microbattery is based on the all solid-state thin-film technology, first developed by Bates et al. [17]. The active components are typically less than 20 μm thin and the solid-state lithium phosphorus oxynitride (LiPON) separator is only a few micrometers thick in order to compensate for the low conductivity of the LiPON electrolyte. However, because of poor packaging, most of the cells exhibit poor energy density (Wh/l). The core concept behind the 3D battery is to develop novel nanoarchitecture by more efficient use of available space in the z direction, resulting in interpenetrating electrodes. The concepts, shown schematically in Figure 6.6, are the topics of current research. Scaling of these architectures to realistic battery sizes is not yet proven. 3D architectures are clearly optimal when one is constrained in volume (e.g. for thin-film cells or smart motes). Fabrication strategies play a key role

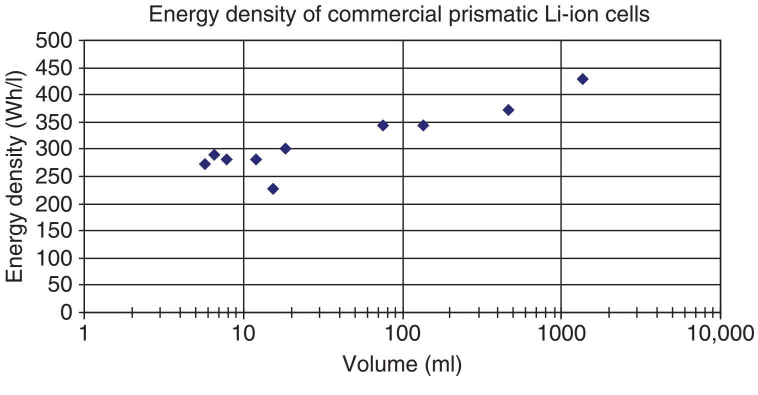

FIGURE 6.5 Energy density decreases with cell size in commercial prismatic Li-ion cells. ((Table 35.13) D. Linden, and T. B. Reddy, Eds. *Energy Density Calculated Based on Data in Handbook of Batteries*, 3rd ed., McGraw Hill, New York, p. 35.36.)

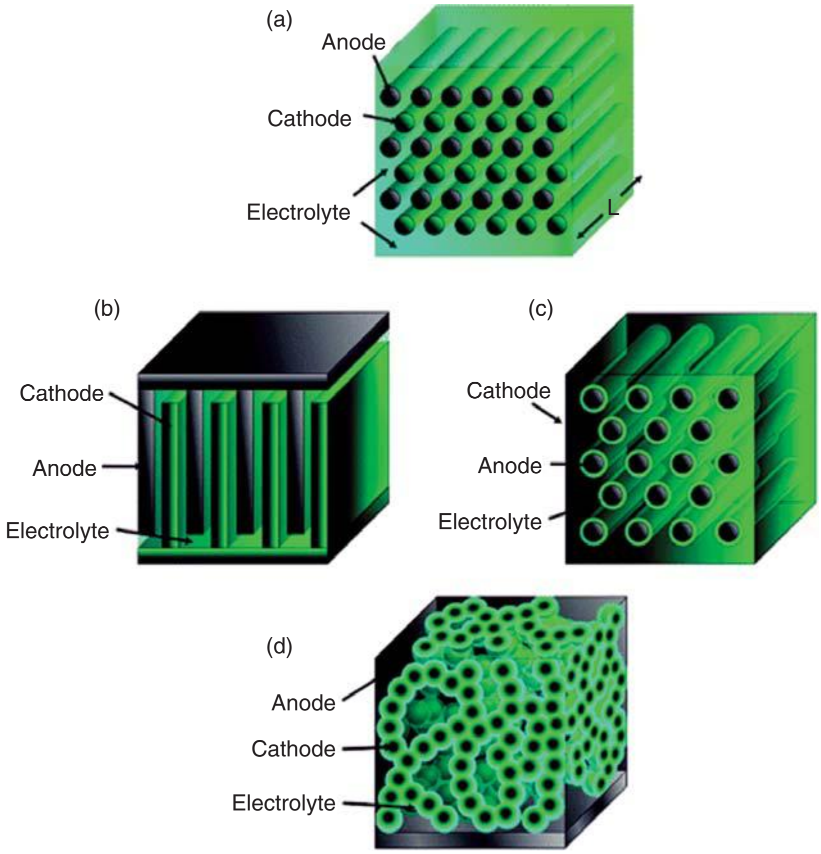

FIGURE 6.6 Schematic representation of 3D architectures including (a) an array of interdigitated cylindrical cathodes and anodes; (b) an interdigitated plate array of cathodes and anodes; (c) a rod array of cylindrical anodes (cathodes) with a thin layer of ion conducting electrolyte with the remaining free volume filled with cathode (anode) material; (d) a sponge architecture in which the solid network of the "sponge" serves as both the cathode and the current collector, it is coated with a thin electrolyte and the remaining free volume is filled with an interpenetrating, continuous anode. [See Figure 6.2 in Reference 19, page 4466].

here; novel techniques such as the use of Langmuir–Blodgett thin films, layer-by-layer self-assembly, template synthesis, and semiconductor processing (e.g. lithography and etching to define microstructures followed by and deposition to add materials) are not yet available or are prohibitively expensive. It is important to note that the periodic arrangements of 3D configured anodes and cathodes lead to nonuniform current distributions [18], while interpenetrating, conformal, aperiodic arrangements do not.

Finally, Belcher et al. in MIT [20] reported virus assembled electrochemically active cobalt oxide for use in lithium batteries. However, the complex command and control needed for viruses to self-assemble themselves to form the positive and negative electrodes remain to be demonstrated, in order to achieve the ultimate goal of virus self-assembled microbattery.

6.3.2 Membranes, Separators, and Electrolytes

Self-assembly of nanostructures may produce advanced functional materials for this application as well. Shape control can allow synthesis of tubular structures with enhanced ionic conductivity. Surfactant templating methods [21] have produced interesting materials for battery electrolytes and the same technology could be used for fuel cell electrolytes. This approach could also be applied to membranes in metal/air batteries (sometimes termed *semi-fuel cells*) to allow selective transport of oxygen while rejecting carbon dioxide and water. Additionally, commercialization of high energy rechargeable systems (e.g. Li/sulfur and Li/air) would be enabled by stabilizing the lithium interface, which results in cycle life and safety improvements.

Although nanotechnology may not play a role in the chemistry of liquid electrolytes, it can be potentially exploited to improve separator performance. For example, new separator materials designed with large numbers of nanoscale pores may allow for thinner materials with enhanced ionic conductivity. Opportunities also include tailoring the separator nanostructure using organic/inorganic composite electrolytes to improve both physical stability (i.e. prevent physical contact of the electrodes) and conductivity [22]. Self-assembly processes may also be effective in depositing extremely thin separator layers on anode and cathode surfaces. If both the pore size/shape and the pore chemistry could be controlled effectively, one can envision ions rapidly moving through empty channels, thereby forming a “liquid-like” separator without any liquid.

The ionic conductivity of solid-state electrolytes is generally far less than that of liquid electrolytes due to limited ion mobility and the hopping of charge from one unit cell to the next. However, by making the electrolyte layers extremely thin and stable, effective (albeit low power density) batteries can be made; for example, LiPON functions as a micrometer-scale electrolyte in rechargeable thin-film lithium batteries [23]. Optimization of the nanostructure of these materials may lead to increased conductivity (grain boundary/defect diffusion) and thinner layers without shorting (again leading to enhanced conductivity), and thus to improved power capability.

6.3.3 Electrodes and Electrocatalysts for Fuel Cells

These components are critical to the function of a fuel cell since they catalyze the electrochemical reduction of oxygen at the cathode and the oxidation of fuel at the anode. Breakthroughs in electrocatalysts might revolutionize fuel cells by giving them fuel flexibility and increasing power output, as well as by increasing their tolerance to chemical species that tend to poison them (e.g. carbon monoxide or sulfur-containing moieties).

New synthetic methodologies might allow for the control of fuel cell electrode microstructures. Nanostructured catalysts may enhance reaction kinetics by dramatically increasing electrode surface area and restricting reactions to confined regions of the active surface. In one study, high catalytic activity resulted from high active surface area of the catalysts supported within an ultraporous electrode nanoarchitecture [24]. High-surface-area materials are extremely reactive, which often causes problems during synthesis (e.g. nanophase metals are often capped with organic ligands after synthesis to prevent sintering reactions). The goal is to maintain the high surface area of nanostructured catalysts, while avoiding agglomeration, sintering, or restructuring during use. Self-assembly on the nanoscale using shape control of catalytic materials (e.g. bimetallic catalysts) might also be important [25].

6.3.4 Thermoelectric Devices

Temperature differences can be used to generate power. The power density scales with temperature difference. A 5 °C temperature difference can generate 40-80 μW/cm^2 with existing thermoelectric technology. This temperature difference can be generated from man-made sources (parasitic devices placed on warm surfaces such as automobile engines, pipelines, and heaters), environmental gradients (in the soil, water, or at their interface), and within animals (one company has announced one such device for human implantation) [26].

While static conversion of heat into electricity has been an area of research for many decades, the promise of producing tailored nanostructures has prompted renewed interest in several energy conversion schemes. Nanotechnology offers the potential for improved efficiencies, since shrinking the characteristic dimensions of a device to nanometer length scales influences electron and phonon behavior. The efficiency of thermoelectric devices can also be characterized by the figure of merit, ZT, where Z is the power factor and T is the absolute temperature. A limitation of thermoelectrics designed around standard bulk materials is that most metallic conductors (high σ materials) have low Seebeck coefficients (a few microvolt per kelvin, whereas ≥ 100 μV/K would be more desirable), while the electron and phonon contributions to thermal conductivity make it difficult to achieve both high σ and low κ in the same material. As a result, the ZT remained at 1 or less for the last 40 years. Recently, researchers from Research Triangle Institute were able to increase the ZT to about 2.4 in p-type thin-film superlattices of Bi_2Te_3/Sb_2Te_3 [27]. The nanostructured superlattice layers vary from 1 to 5 nm. The thermal conductivity and the electrical resistivity are reduced due to blocked phonon transmission and enhanced carrier mobility, respectively, in the nanothick superlattice layer.

Quantum confinement of electronic charge carriers within regions of reduced dimensionality has the potential to increase the power factor [28]. Increased phonon scattering that occurs when interfaces are separated by distances compared to phonon wavelengths can reduce the lattice thermal conductivity [27]. These approaches require tailored nanometer-scale materials synthesis techniques, as the critical dimension for confinement is ~10 nm. One can reduce dimensionality in one dimension (confinement in a plane) to three dimensions (confinement in a "quantum dot"). Improved materials synthesis and characterization techniques on the nanoscale, as well as advances in the theory and characterization of nanodimensional solids, are required.

6.3.5 Photovoltaics

The energy conversion efficiency of photovoltaics (including thermophotovoltaic or TPV devices) may also be increased by effects associated with reduced dimensionalities on the nanometer scale. Photonic lattices have sharp absorption and emission peaks at their photonic band edges. By tuning the emission peak of a photonic crystal (emitter) to the bandgap energy of a photodiode (energy conversion device), one could increase the overall conversion efficiency of TPVs [29]. The conversion efficiency might also be increased by evanescent coupling of an infrared emitter to a photodiode in very close (subwavelength) proximity [30]. Another approach to improve the photovoltaic (PV) efficiency is by increasing the intrinsic quantum efficiency of the PV material via the use of quantum dots. The exact mechanism for the quantum dot enhancement is still not well understood, though it is speculated to be related to enhanced electron–hole interaction due to quantum confinement. In conventional PV material such as Si, one electron–hole pair (or exciton) is generated per photon. The feasibility of generating multiple excitons per photon was demonstrated in various quantum dots materials such as PbSe quantum dots, leading to multiple increase in quantum efficiency [31]. However, it remains a challenge to design high efficiency PV devices based on the quantum dots, and PV device efficiency enhancement over 100% has yet to be demonstrated. Nanoscale optimization of the interfaces between disparate materials in organic light-emitting diodes (OLEDs), organic solar cells, and thin-film solar cells represents another opportunity. Nanosize oxide particles (e.g. TiO_2 or ZnO) with organic sensitizers bound to the surface are proposed as a new class of solar cells, and controlled interfaces are the key to improving the efficiency of these devices [32]. Modeling advancements are required to direct the materials synthesis and processing efforts.

6.4 RESEARCH DIRECTIONS

Nanotechnology enables the rational design of power source devices and structures with optimized storage, conductivity, density, and optical and electronic properties. The potential for tailoring of chemical composition and morphology at the nanometer scale will provide the opportunity for unprecedented control of materials properties. The following are specific areas that need to be investigated:

1. Nanomaterial synthesis and characterization.
    - Performance optimization is a balancing act between electron/ion/mass transport and electrode kinetics, but independent control of transport multifunction is difficult to do with bulk materials. In batteries, disorder improves mass transport of insertion ions, but sufficient order (even on the nanoscale) must be retained to move electrons. As the particle size is reduced, the relative fraction of atoms at the surface significantly increases, to the point that three-dimensional particles begin to exhibit the characteristics of two-dimensional objects.
    - By creating 2D structures with specific surface chemistry and morphology, one can control the interface between materials or phases, so as to elicit the desired behavior. Nanomaterials plus interface chemical approach have enabled the rapid implementation of the insulating $LiFePO_4$ phase in practical Li-ion cells and allowed us to foresee the use of Si as an alternative to the nanostructured Sn-graphite-based negative electrode. There exists also the possibility to tailor the optical and electronic characteristics of a material, which strongly influence energy conversion processes, allowing us to envision the production of improved catalysts and electrolytes for fuel cells, as well as improved thermoelectrics and photovoltaics.
2. Nanoarchitectures to develop novel energy conversion and storage devices.
    - Nanotechnology will enable realization of devices with increased energy or power. For example, by maximizing the interfacial area between the anode and cathode while minimizing their separation, one can increase the power density of a cell dramatically. Improvements in energy density are attained by processing very thin electrolytes and better packing of materials. Such multifunctional concepts have the potential to further decrease the size and weight of a system for a given mission.

- Nanomachining technology, combined with new and improved materials, opens up opportunities both for improving the performance of energy harvesting schemes and for realizing highly miniaturized versions of systems that are familiar at a larger scale.

Creation of exciting new materials and architectures for batteries, electrochemical capacitors, fuel cells as well as other energy conversion devices holds the potential to meet the intense need for increased energy and power for electronic devices of interest to homeland security community.

REFERENCES

1. National Academy of Science. *Nanotechnology for the Intelligence Community*, National Research Council of the National Academies, National Academy Press, Washington, DC, May 2005.
2. Plitz, I., Dupasquier, A., Badway, F., Gural, J., Pereira, N., Gmitter, A., and Amatucci, G. G. (2006). The design of alternative nonaqueous high power chemistries. *Appl. Phys.* **A82**, 615–626. DOI: 10.1007/s00339-005-3420-0.
3. http://www.technewsworld.com/story/hardware/41889.html [March 30, 2005].
4. Herle, P. S., Ellis, B., Coombs, N., and Nazar, L. F. (2004). Nano-network electronic conduction in iron and nickel olivine phosphates. *Nat. Mater.* **3**, 147–152.
5. http://www.a123systems.com/newsite/index.php#/products/cells26650/, 2008.
6. Amatucci, G. G., Badway, F., Du Pasquier, A., and Zheng, T. (2001). An asymmetric hybrid nonaqueous energy storage cell. *J. Electrochem. Soc.* **148**, A930–A939.
7. Zheng, J. P., Cygan, P. J., and Jow, T. R. (1995). Hydrous ruthenium oxide as an electrode material for electrochemical capacitors. *J. Electrochem. Soc.* **142**, 2699–2703.
8. Dmowski, W., Egami, T., Swider-Lyons, K. E., Love, C. T., and Rolison, D. R. (2002). Local atomic structure and conduction mechanism of nanocrystalline hydrous RuO_2 from X-ray scattering. *J. Phys. Chem. B* **106**, 12677–12683.
9. Winter, M., and Besenhard, J. O. (1999). Rationalization of the low-potential reactivity of 3d-metal-based inorganic compounds toward Li. *Electrochim. Acta* **45**, 31. See also Poizot, P., Laruelle, S., Grugeon, S. Dupont, L., and Tarascon, J.-M. (2000). Nano-sized transition-metal oxides as negative-electrode materials for lithium-ion batteries. *Nature* **407**, 496–499.
10. Amatucci, G. G., and Pereira, N. (2007). Fluoride based electrode materials for advanced energy storage devices. *J. Fluor. Chem.* **128**(4), 243–262. DOI:10.1016/j.jfluchem.2006.11.016.
11. (a) Badway, F., Mansour, A., Plitz, I., Pereira, N., Weinstein, L., Yourey, W., and Amatucci, G. G. (2006). Enabling aspects of metal halide nanocomposites for reversible energy storage. *J. Electrochem. Soc.* **153**, A799; (b) Bervas, M., Yakshinskiy, B. Klein, L. C., and Amatucci, G. G. (2006). Soft-chemistry synthesis and characterization of bismuth oxyfluorides and ammonium bismuth fluorides. *J. Am. Ceram. Soc.* **89**, 645–651.
12. Roberts, G. A., Gross, K. J., Ingersoll, D., Spangler, S. W., and Wang, J. C. (2003). *Silicon/Carbon Composite Negative Electrode Materials*, Sandia National Laboratories SAND Report for Unlimited Release, SAND2002-8627. See also Kevin Bullis, Technology Review Published Online, (25 October 2006) http://www.technologyreview.com/Energy/17653/page2/.
13. http://www.sony.net/SonyInfo/News/Press/200502/05-006E/index.html, 2008.
14. http://www.dailytech.com/Article.aspx?newsid=6094, 2008.
15. http://www.u-picardie.fr/alistore/new_page_2.htm, 2008.

16. http://www.smalltimes.com/Articles/Article_Display.cfm?ARTICLE_ID=267721&p=109, 2008.
17. Bates, J. B., Dudney, N. J., Gruzalski, G. R., and Luck, C. F. (1994). Thin film battery and method for making same. US Patent 5338625.
18. Hart, R. W., White, H. S., Dunn, B., and Rolison, D. R. (2003). 3-D microbatteries. *Electrochem. Commun.* **5**, 120–123.
19. Long, J. W., Dunn, B., Rolison, D. R., and White, H. S. (2004). Three-dimensional battery architectures. *Chem. Rev.* **104**, 4463–4492. DOI 10.1021/cr020740l.
20. Nam, K., Kim, D.-W., Yoo, P. J., Chiang, C.-Y., Meethong, N., Hammond, P. T., Chiang, Y.-M., and Belcher, A. (2006). Sciencexpress/ www.sciencexpress.org/06 April.
21. Kim, H. J., Lee, H. C., Rhee, C. H., Chung, S. H., Lee, K. H., and Lee, H. C. (2003). Alumina nanotubes containing Li of high ion mobility. *J. Am. Chem. Soc.* **125**, 13354–13355.
22. Bronstein, L. M., Joo, C., Karlinsey, R., Ryder, A., and Zwanziger, J. W. (2001). Solid hybrid polymer electrolyte networks: nano-structurable materials for lithium batteries. *Chem. Mater.* **13**, 3678.
23. (a) Bates, J. B., Dudney, N. J., Gruzalski, G. R., Zuhr, R. A., Choudhury, A., Luck, C. F., and Robertson, J. D. (1992). Effects of deposition condition on the ionic conductivity and structure of amorphous lithium. *Solid State Ionics* **647**, 53–56.; (b) Bates, J. B., Dudney N. J., Neudecker, B., Ueda, A., and Evans C. D. (1997). Thin-film lithium and lithium-ion batteries. *J. Electrochem. Soc.* **144**, 524.
24. Anderson, M. L., Stroud, R. M., and Rolison, D. R. (2002). Enhancing the activity of fuel-cell reactions by designing three–dimensional nanostructured architectures: catalyst-modified carbon-silica composite aerogels. *Nano Lett.* **2**, 235–240; correction: *Nano Lett*. 2003, 3, 1321.
25. Approaches to Combat Terrorism (ACT) (2003). *Opportunities for Basic Research, Joint Workshop by The Directorate of the Mathematical and Physical Sciences, NSF and the Intelligence Community*, National Science Foundation, http://www.mitre.org/public/act/10_22_final.pdf).
26. http://adsx.com/prodservpart/thermolife.html, 2008.
27. Venkatasubramanian, R., Silvola, E., Colpitts, T., and O'Quinn, B. (2001). Thin-film thermoelectric devices with high room-temperature figures of merit. *Nature* **413**, 597–602. DOI: 10.1038/35098012.
28. (a) Hicks, L. S. and Dresselhaus, M. S. (1993). Effect of quantum-well structures on the thermoelectric figure of merit. *Phys. Rev. B* **47**, 12727–12731. **DOI:** 10.1103/PhysRevB.47.12727; (b) Majumdar, A. (2004). Thermoelectricity in semiconductor nanostructures. *Science* **303**, 777–7778.
29. Fleming, J. G., Lin, S. Y., El-Kady, I., Biswas, R., and Ho, K. M. (2002). All-metallic three-dimensional photonic crystals with a large infrared bandgap. *Nature* **417**, 52–55.
30. DiMatteo, R. S., Greiff, P., Finberg, S. L., Young-Waithe, K. A., Choy, H. K. H., Masaki, M. M., and Fonstad, C. G. (2001). Enhanced photogeneration of carriers in a semiconductor via coupling across a nonisothermal nanoscale vacuum gap. *Appl. Phys. Lett.* **79**, 1894.
31. Schaller, R. D., and Klimov, V. I. (2004). High efficiency carrier multiplication in PbSe nanocrystals: implications for solar energy conversion. *Phys. Rev. Lett.* **92**, 186601. DOI:10.1103/PhysRevLett.92.186601.
32. Grätzel, M. (2001). Sol-gel processed TiO_2 films for photovoltaic applications. *J. Sol-Gel Sci. Technol.* **22**, 7–13.

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