Bahman Zohuri · Patrick McDaniel

Advanced Smaller Modular Reactors

An Innovative Approach to Nuclear Power

Springer

Advanced Smaller Modular Reactors

Bahman Zohuri • Patrick McDaniel

Advanced Smaller Modular Reactors

An Innovative Approach to Nuclear Power

Springer

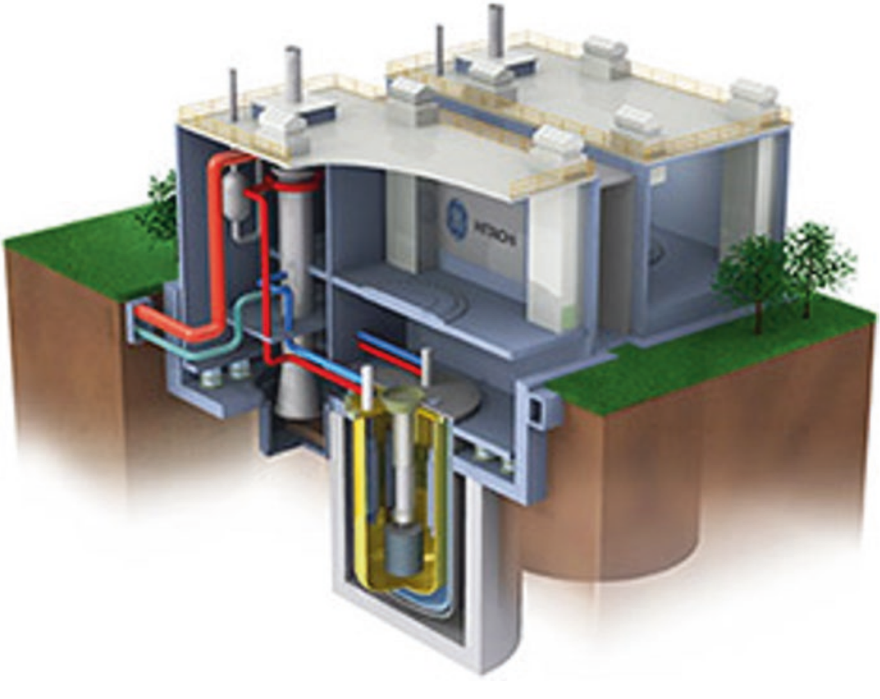
Bahman Zohuri
Electrical and Computer Engineering
Department
University of New Mexico
Albuquerque, NM, USA

Patrick McDaniel
Chemical and Nuclear Engineering
Department
University of New Mexico
Albuquerque, NM, USA

ISBN 978-3-030-23681-6 ISBN 978-3-030-23682-3 (eBook)
https://doi.org/10.1007/978-3-030-23682-3

© Springer Nature Switzerland AG 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland



GE
HITACHI

This book is dedicated to my son Sasha and Grandson Darius.

Bahman Zohuri

This is also dedicated to Dr. Harold Lurie and Dr. Alexander Sesonske who both inspired me at two different points in my career.

Patrick McDaniel

Preface

Advanced small modular reactors (SMRs) range in size up to 300 megawatts electric (MWe), employ modular construction techniques, ship major components from factory fabrication locations to the plant site by rail or truck, and include designs that simplify plant site activities required for plant assembly.

These are a key part of the Department of Energy's goal to develop safe, clean, and affordable nuclear power options. The advanced SMRs, which are currently under development in the United States, represent a variety of sizes, technology options, and deployment scenarios. These advanced reactors, envisioned to vary in size from a couple megawatts up to hundreds of megawatts, can be used for power generation, heat processing, desalination, or other industrial uses. SMRs can employ light water as a coolant or other non-light water coolants such as gas, liquid metal, or molten salt.

Advanced SMRs offer many advantages, such as relatively small size, reduced capital investment, ability to be sited in locations not possible for larger nuclear plants, and provisions for incremental power additions. SMRs also offer distinct safeguards, security, and nonproliferation advantages.

The Department of Energy (DOE) has long recognized the transformational value that advanced SMRs can provide to the nation's economic, energy security, and environmental outlook. Accordingly, the Department has provided substantial support to the development of light water-cooled SMRs, which are under licensing review by the Nuclear Regulatory Commission (NRC) and will likely be deployed in the next 10–15 years. The DOE is also interested in the development of SMRs that use nontraditional coolants such as liquid metals, salts, and helium because of the safety, operational, and economic benefits they offer.

The Department of Energy recently issued a multi-year cost-shared funding opportunity to support innovative, domestic nuclear, industry-driven concepts that have high potential to improve the overall economic outlook for nuclear power in the United States. This funding opportunity will enable the development of existing, new, and next-generation reactor designs, including SMR technologies.

The scope of the funding opportunity is very broad and solicits activities involved in finalizing the most mature SMR designs; developing manufacturing capabilities and techniques to improve cost and efficiency of nuclear builds; developing plant structures, systems, components, and control systems; and addressing regulatory issues and other technical needs identified by the industry. The funding opportunity will provide awards sized and tailored to address a range of technical and regulatory issues impeding the progress of advanced reactor development.

Initiated in FY2012, the SMR Licensing Technical Support (LTS) Program works with industry partners, research institutions, national laboratories, and academia to accelerate the certification, licensing, and siting of domestic advanced SMR designs and to reduce economic, technical, and regulatory barriers to their deployment. FY2017 was the last year of planned funding for this successful program, but the activities will be completed over the next several years as certification and licensing efforts are completed.

In this book, we are trying to explore the advanced small modular reactor (aSMR), and we have started with the following chapters:

Chapter 1 describes early substance that man found, used, and relied on for the luxuries of light, heat, and cooking as we historically know. Today, we take all these luxuries for granted. At the flick of a switch, a push of a button, or the turn of a knob, we can have instant power. Electricity plays a huge part in our everyday lives. Whether it is at home, school, the local shopping center, or our workplace, our daily routines rely heavily on the use of electricity. From the time we wake up in the morning until we hit the pillow at night, our daily life is dependent on electricity. The alarm we have to turn off each morning runs on electricity. The light in our bedroom, the hot shower we take before breakfast, Dad's electric razor, all these things need electricity in order to function. Even our first meal of the day is heavily dependent on electricity. The fridge that keeps all our food cool and fresh needs electricity to run, or the grill that cooks your bacon and eggs also needs power to operate. This power generally (unless you have gas stove) comes from electricity. Electricity not only plays a big part in our daily lives at home, but it is extremely important for all the things that go on in the world around us in our modern life, such as the industry that we depend on and communication in the form of radio, television, email, the Internet, etc. Transport is another aspect of our daily life that depends on electricity to some degree.

Chapter 2 goes over energy and its broad definition. Energy is broadly defined as the ability to produce a change from the existing conditions. Thus, the term energy implies that a capacity of action is present. The evaluation of energy is done by measuring certain effects that are classified by descriptive names, and these effects can be produced under controlled conditions. For example, mass that is located at certain position may have a potential energy or if the same mass is in motion, then, it may possess the kinetic energy, due to its temperature and pressure it may posses internal energy. The internal energy can be measured by the change potential energy experienced by an external load.

Chapter 3 talks about the economics of advanced small modular reactor. Developments in the US economy that will affect the nuclear power industry in the coming years include the emergence of new nuclear technologies, waste disposal issues, proliferation concerns, streamlining of nuclear regulation, possible transition to a hydrogen economy, policies toward national energy security, and environmental policy. These developments will affect both the competitiveness of nuclear power and appropriate nuclear energy policies.

Chapter 4 describes advanced power conversion system for small modular reactors, where the major growth in electricity production industry in the last 30 years is centered on the expansion of natural gas power plants based on gas turbine cycles. The most popular extension of the simple Brayton gas turbine has been the combined cycle power plant with the open Air-Brayton cycle serving as the topping cycle and the steam Rankine cycle serving as the bottoming cycle for new generation of nuclear power plants that are known as GEN-IV. The Air-Brayton cycle is an open-air cycle, while the Steam-Rankine cycle is a closed cycle. The Air-Brayton cycle for a natural gas-driven power plant must be an open cycle, where the air is drawn in from the environment and exhausted with the products of combustion to the environment. This technique is suggested as an innovative approach to GEN-IV nuclear power plants in the form and type of small modular reactors (SMRs). The hot exhaust from the Air-Brayton cycle passes through a heat recovery steam generator (HSRG) prior to exhausting to the environment in a combined cycle. The HRSG serves the same purpose as a boiler for the conventional steam Rankine cycles.

Chapter 5 takes into consideration the advanced small modular reactor and environment and goes over pros and cons of such reactors. Some proponents of nuclear power are advocating for the development of small modular reactors (SMRs) as the solution to the problems facing large reactors, particularly soaring costs, safety, and radioactive waste. Unfortunately, small-scale reactors cannot solve these problems and would likely exacerbate them. There has been a proliferation of proposed SMR designs, but none have applied for certification by the Nuclear Regulatory Commission yet. The NRC says that it expects to receive its first SMR design certification application in 2012. There are three general types of SMRs being discussed for certification and possible deployment in the United States.

Chapter 6 involves topic on safety and nonproliferation aspect of advanced small modular reactor. Safety is matter it concern and is a national responsibility of each state or nation having the capability to design a reactor core for nuclear power plants. International standards and approaches to safely promote consistency, help provide assurance that nuclear- and radiation-related technologies are used safely, and facilitate national and international technical cooperation between government regulatory and industry of each nation with nuclear power capabilities.

Chapter 7 speaks about reliable electricity grids and renewable source of energy. The electric power grid is rapidly changing due to the penetration of renewable energy sources, primarily solar and wind, into the supply mix. This has major economic implications and will greatly influence the demand curves that nuclear or fossil plants will see in the future. The only solution for taking advantage of intermittent sources like solar and wind is to develop some form of energy storage. Both electrical and heat forms of storage may be possible. Ultimately, the cost will determine how each of these storage technologies is implemented. Some power conversion systems will be more efficient than others.

Chapter 8 goes over the subject of integration energy storage with advanced small modular reactors, where they are used as source of producing energy for generating electricity. Nuclear reactors produce heat and thus can couple to heat storage systems to provide dispatchable electricity while the reactor operates at full power. Six classes of heat storage technologies couple to light water reactors with steam cycles. Firebrick Resistance-Heated Energy Storage (FIRES) converts low-price electricity into high-temperature stored heat for industry or power. FIRES and brick recuperators coupled to nuclear Brayton power cycles may enable high-temperature reactors to buy electricity when prices are low and sell electricity at higher price.

Finally, Chapter 9 briefly goes over the design and analysis of core design for small modular reactor from holistic point of view. The pronuclear energy and advocates are lobbying that the sustainable development of the world's energy sector cannot be achieved without the extensive use of nuclear energy and the advantages of nuclear-related technologies, including the upcoming new generation of the small modular reactors in the near future horizon. The dawn of these SMRs requires new design and analysis no matter if they are falling into light water reactor (LWR), pressurized water reactor (PWR), or even multi-application small light water reactor (MASLWR) categories, depending on the vendor involved with these new technologies and consequently safety standards and their nonproliferation requirements as well. This chapter visits these standards for core design and generally elaborated on them with understanding that readers need to refer just beyond this book and this chapter for more details.

We, as authors, hope that this book will provide our readers a very broad background on the subject of advanced small modular reactor and these readers go away with a better understanding of the subject that meant for title of this book.

Albuquerque, NM, USA — Bahman Zohuri
Albuquerque, NM, USA — Patrick McDaniel
2016

Acknowledgment

I am indebted to the many people who aided, encouraged, and supported me beyond my expectations. Some are not around to see the results of their encouragement in the production of this book, yet I hope they know my deepest appreciations. I especially want to thank my friend Bill Kemp, to whom I am deeply indebted. He has continuously given his support without hesitation and has always kept me going in the right direction.

Above all, I offer very special thanks to my late mother and father and to my children, in particular, my son Sasha and my grandson Darius. They have provided constant interest and encouragement, without which, this book would not have been written. Their patience with my many absences from home and long hours in front of the computer to prepare the manuscript are especially appreciated.

Bahman Zohuri

As my contributions to this book have come since I have been widowed, I can only acknowledge my wife Nancy Ries for her support while she was alive. But I would very much like to acknowledge the professional support I have received from my collaborator, and close personal friend, Professor Cassiano de Oliveira of the Nuclear Engineering faculty at the University of New Mexico. He has consistently provided advice that has guided my efforts.

Patrick McDaniel

Contents

About the Authors

Bahman Zohuri is currently at University of New Mexico, Department of Electrical and Computer Engineering, while working for Galaxy Advanced Engineering, Inc., a consulting firm that he started in 1991 when he left both the semiconductor and defense industries after many years working as a chief scientist. After graduating from the University of Illinois in the field of physics and applied mathematics, he went to the University of New Mexico, where he studied nuclear engineering and mechanical engineering. He joined Westinghouse Electric Corporation, where he performed thermal hydraulic analysis and studied natural circulation in an inherent shutdown heat removal system (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shutdown system for secondary loop heat exchange. All these designs were used in nuclear safety and reliability engineering for a self-actuated shutdown system.

He designed a mercury heat pipe and electromagnetic pumps for large pool concepts of an LMFBR for heat rejection purposes around 1978, when he received a patent for it. He was subsequently transferred to the Defense Division of Westinghouse, where he oversaw dynamic analysis and methods of launching and controlling MX missiles from canisters. The results were applied to MX launch seal performance and muzzle blast phenomena analysis (i.e., missile vibration and hydrodynamic shock formation). He was also involved in analytical calculations and computations in the study of nonlinear ion waves in rarefying plasma. The results were applied to the propagation of so-called soliton waves and the resulting charge collector traces in the rarefaction characterization of the corona of laser-irradiated target pellets.

As part of his graduate research work at Argonne National Laboratory, he performed computations and programming of multi-exchange integrals in surface physics and solid-state physics. He earned various patents in areas such as diffusion processes and diffusion furnace design while working as a senior process engineer at various semiconductor companies, such as Intel Corp., Varian Medical Systems, and National Semiconductor Corporation. He later joined Lockheed Martin Missiles and The Aerospace Corporation as senior chief scientist and oversaw research and development (R&D) and the study of the vulnerability, survivability, and both radiation and laser hardening of the different components of the Strategic Defense Initiative, known as Star Wars.

This included payloads (i.e., IR sensor) for the Defense Support Program, the Boost Surveillance and Tracking System, and the Space Surveillance and Tracking Satellite against laser and nuclear threats. While at Lockheed Martin, he also performed thermomechanical analyses, analyses of laser beam characteristics and nuclear radiation interactions with materials, transient radiation effects in electronics, electromagnetic pulses, system-generated electromagnetic pulses, single-event upset, blast, hardness assurance, maintenance, and semi-conductor device performance.

He spent several years as a consultant at Galaxy Advanced Engineering serving Sandia National Laboratories, where he supported the development of operational hazard assessments for the Air Force Safety Center in collaboration with other researchers and third parties. Ultimately, the results were included in Air Force Instructions issued specifically for directed energy weapons operational safety. He completed the first version of a comprehensive library of detailed laser tools for airborne lasers, advanced tactical lasers, tactical high-energy lasers, and mobile/tactical high-energy lasers, for example.

He also oversaw SDI computer programs, in connection with Battle Management C^3I and artificial intelligence, and autonomous systems. He is the author of several publications and holds several patents, such as for a laser-activated radioactive decay and results of a through-bulkhead initiator.

Patrick McDaniel is currently adjunct and research professor at the Department of Nuclear Engineering, University of New Mexico. He began his career as a pilot and maintenance officer in the USAF. After leaving the Air Force and obtaining his doctorate at Purdue University, he worked at Sandia National Laboratories in fast reactor safety, integral cross-section measurements, nuclear weapons vulnerability, space nuclear power, and nuclear propulsion. He left Sandia to become the technical leader for Phillips Laboratory's (became part of Air Force Research Laboratory) Satellite Assessment Center. After 10 years at PL/AFRL, he returned to Sandia to lead and manage DARPA's Stimulated Isomer Energy Release Project. While at Sandia, he worked on the Yucca Mountain Project and DARPA's Classified UER-X Program. Having taught at the University of New Mexico in the Graduate Nuclear Engineering Program for 25 years, when he retired from Sandia in early 2009, he joined the faculty at the University of New Mexico full time. He has worked on multiple classified and unclassified projects in the application of nuclear engineering to high-energy systems. Moreover, he holds a BS degree in Engineering Science from the USAF Academy, an MS in Mechanical Engineering (nuclear option) from Cal Tech, a PhD in Nuclear Engineering from Purdue University, and an MS in Resource Management from the Industrial College of the Armed Forces.

Chapter 1
The Electricity: An Essential Necessity in Our Life

Early man relied on fire for the luxuries of light, heat, and cooking. Today, we take all these luxuries for granted. At the flick of a switch, a push of a button, or the turn of a knob, we can have instant power. Electricity plays a huge part in our everyday lives. Whether it is at home, school, the local shopping center, or our workplace, our daily routines rely heavily on the use of electricity. From the time we wake up in the morning until we hit the pillow at night, our daily life is dependent on electricity. The alarm we have to turn off each morning runs on electricity. The light in our bedroom, the hot shower we take before breakfast, Dad's electric razor, all these things need electricity in order to function. Even our first meal of the day is heavily dependent on electricity. The fridge that keeps all our food cool and fresh needs electricity to run or the grill that cooks your bacon and eggs also needs power to operate. This power generally (unless you have gas stove) comes from electricity. Electricity not only plays a big part in our daily lives at home, but it is extremely important for all the things that go on in the world around us in our modern life, such as industry that we depend on and communication as in the form of radio, television, email, the Internet, etc. Transport is another aspect of our daily life that depends on electricity to some degree.

1.1 Introduction

The Human Development Index (HDI) was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone. The HDI can also be used to question national policy choices, asking how two countries with the same level of GNI per capita can end up with different human development outcomes. These contrasts can stimulate debate about government policy priorities.

The Human Development Index (HDI) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being

B. Zohuri, P. McDaniel, *Advanced Smaller Modular Reactors*,
https://doi.org/10.1007/978-3-030-23682-3_1

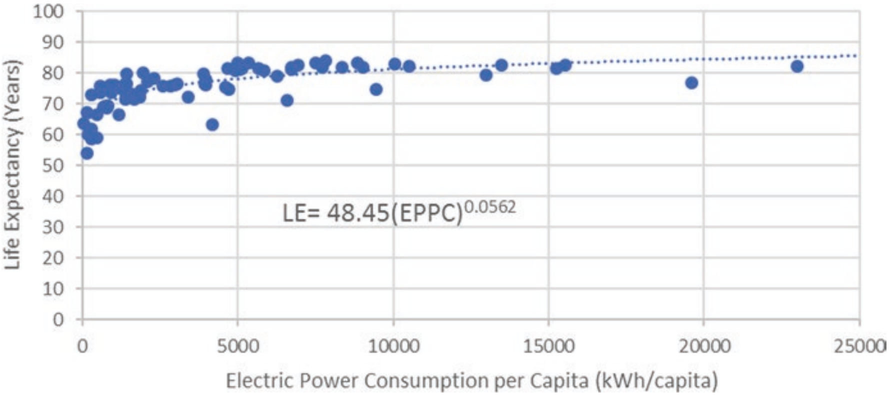


Fig. 1.1 Life expectancy vs. electric power consumption per capita [1]

knowledgeable, and have a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions.

The health dimension is assessed by life expectancy at birth, and the education dimension is measured by means of years of schooling for adults aged 25 years and more and expected years of schooling for children of school entering age. The standard of living dimension is measured by gross national income per capita.

The HDI simplifies and captures only part of what human development entails. It does not reflect on inequalities, poverty, human security, empowerment, etc. The HDRO offers the other composite indices as broader proxy on some of the key issues of human development, inequality, gender disparity, and poverty.

Actually, there is a correlation between life expectancy and electric power consumption as shown in Fig. 1.1. Below 5000 kWh per year per capita, the correlation is strong; above 5000 kWh per year per capita, it is not as strong, but it still exists.

In fact, only about one-quarter of more than 4 billion people on this planet live in countries where the average food consumption is well above physiological needs, where infant mortality is relatively low (typically below 25 per 1000 live births), life expectancy is high (around 70 years), and literacy approaches 100%. These are the world's most developed nations: one-quarter of mankind consuming four-fifths of the commercial energy consumed annually and enjoying a quality of life unsurpassed in history.

For the remaining three-quarters of the human population, conditions are painfully different. The overwhelming majority of these people are illiterate or semiliterate poor villagers surviving on less than adequate diets, whose infant mortality is an order of magnitude higher than in the developed world and whose life expectancy is as much as three decades shorter. The difficult present and less than promising future of this developing world or, as some prefer, the less developed countries (LDC) or underdeveloped Third World is, to a very large extent, the result of relatively low consumption of commercial energy.

In developing countries, agriculture is the main source of biomass fuel, as well as one of the main energy-consuming sectors. The energy captured through agriculture in crops and crop residues provides food for people and fodder for draft animals; dung and crop residues are used for cooking and heating [2].[1] During the past two decades, these traditional energy sources have been supplemented by the use of coal, oil, and electricity in agriculture, transport, industry, and the domestic sectors. The most striking feature of energy use in the Third World is that the amount of useful work which the poor obtain from the energy they use is relatively small [3]. When the inputs to agriculture (including directly applied energy) are increased properly, the energy outputs per worker and per unit of land increase. Energy obtained from the consumption and sale of crops is, in turn, needed to increase the input to agriculture to raise crop yields, extend irrigated land, increase multi-cropping, mechanize construction and repairs of water projects, build modern roads, and, in general, improve the quality of life of the peasants. The rate with which the developing countries move toward the distant goal of rural modernization is largely determined by the direct and indirect energy flows into agriculture, which may be expected to make up a larger fraction of energy consumption in the future than at present.

The standard of living or quality of life achieved in any community and for any group of people may be measured, for practical purposes, by the quantity of total energy used per capita [4]. It has been widely recognized that the preceding statement is more appropriate for societies in which the production and distribution of energy is secure and widely spread than for LDCs.

1.2 Cost of Generation Electricity Today

One of the first questions that come to our mind about the necessity of electricity for our day-to-day life is that:

> How much does it cost to generate electricity with different types of power plants?

The Annual Energy Outlook 2014 (AEO2014), prepared by the US Energy Information Administration (EIA), presents long-term annual projections of energy supply, demand, and prices focused in the United States through 2040, based on results from EIA's National Energy Modeling System (NEMS). NEMS enables EIA to make projections under alternative, internally consistent sets of assumptions, the results of which are presented as cases. The analysis in AEO2014 focuses on five primary cases: a reference case, low and high economic growth cases, and low and high oil price cases. Results from a number of other alternative cases also are presented, illustrating uncertainties associated with the reference case projections. EIA

---

[1] A mill is equal to 1/000 of a U.S. dollar, or 1/10 of one cent. Mills per kilo-watt-hour (kWh) equals dollars per mega-watt-hour (mWh). To convert mills per kWh to cents per kWh, divide mills per kWh by 10

1 mill/kWh =0.1 cent/kWh
1 mill = 0.1 cents = 0.001 dollars
1 MW = 1000 kW
1 mill/kWh = 1 dollar/MWh

published an early release version of the AEO2014 reference case in December 2013. The projections in the US Energy Information Administration's (EIA's) Annual Energy Outlook 2014 (AEO2014) focus on the factors that shape the US energy system over the long term.

EIA has historical data on the average annual operation, maintenance, and fuel costs for existing power plants by major fuel or energy source types in Table 1.1.

Table 1.1 Average power plant operating expenses for major US investor-owned electric utilities, 2003 through 2013 (mills per kilowatt-hour)

	Operation				Maintenance			
Year	Nuclear	Fossil steam	Hydro electric	Gas turbine and small scale	Nuclear	Fossil steam	Hydro electric	Gas turbine and small scale
2003	9.12	2.74	3.47	3.50	5.23	2.72	2.32	2.26
2004	8.97	3.13	3.88	4.27	5.38	2.96	2.76	2.14
2005	8.26	3.21	3.95	3.69	5.27	2.98	2.73	1.89
2006	9.03	3.57	3.76	3.51	5.69	3.19	2.70	2.16
2007	9.54	3.63	5.44	3.26	5.79	3.37	3.87	2.42
2008	9.89	3.72	5.78	3.77	6.20	3.59	3.89	2.72
2009	10.00	4.23	4.88	3.05	6.34	3.96	3.50	2.58
2010	10.50	4.04	5.33	2.79	6.80	3.99	3.81	2.73
2011	10.89	4.02	5.13	2.81	6.80	3.99	3.74	2.93
2012	12.49	4.38	6.71	2.46	7.32	4.48	4.63	2.75

	Fuel				Total			
Year	Nuclear	Fossil steam	Hydro electric	Gas turbine and small scale	Nuclear	Fossil steam	Hydro electric	Gas turbine and small scale
2003	4.60	17.29	–	43.89	18.95	22.75	5.79	49.66
2004	4.58	18.21	–	45.18	18.93	24.31	6.60	51.59
2005	4.63	21.69	–	55.52	18.15	27.88	6.88	61.10
2006	4.85	23.09	–	53.89	19.57	29.85	6.46	59.56
2007	4.99	23.88	–	58.75	20.32	30.88	9.32	64.43
2008	5.29	28.43	–	64.23	21.37	35.75	9.67	70.72
2009	5.35	32.30	–	51.93	21.69	40.48	8.38	57.55
2010	6.68	27.73	–	43.21	23.98	35.76	9.15	48.74
2011	7.01	27.08	–	38.80	24.70	35.09	8.88	44.54
2012	7.61	28.34	–	30.45	27.42	37.20	11.34	35.67

Hydroelectric category consists of both conventional hydroelectric and pumped storage

Gas turbine and small-scale category consists of gas turbine, internal combustion, photovoltaic, and wind plants

Notes: Expenses are average expenses weighted by next generation. A mill is a monetary cost and billing unit equal to 1/1000 of the US dollar (equivalent to 1/10 of one cent)

Total may not equal to the sum of components due to independent rounding

Sources: Federal Energy Regulatory Commission, FERC Form 1, "Annual Report of Major Electric Utilities, Licensees and Others via Ventyx Global Energy Velocity Suite"

Average Power Plant Operating Expenses for Major US Investor-Owned Electric Utilities, 2001 through 2012 (mills per kilowatt-hour)[1] of the Electric Power Annual.

There are about 19,023 individual generators at about 6997 operational power plants in the United States with a nameplate generation capacity of at least 1 megawatt. A power plant can have one or more generators, and some generators may use more than one type of fuel.

There are currently 61 commercially operating nuclear power plants with 99 nuclear reactors in 30 states in the United States. Thirty-five of these plants have two or more reactors. The Palo Verde plant in Arizona has three reactors and had the largest combined net summer generating capacity of 3937 megawatts (MW) in 2012. Fort Calhoun in Nebraska with a single reactor had the smallest net summer capacity at 479 megawatts (MW) in 2012.

Four reactors were taken out of service in 2013: the Crystal River plant in Florida with one reactor in February, the Kewaunee plant in Wisconsin with one reactor in April, and the San Onofre plant in California with two reactors in June. The Vermont Yankee plant in Vermont, with a single reactor, was taken out of service in December 2014.

The role electricity plays in our lives by enhancing our productivity, comfort, safety, health, and economy is obvious. We live with the benefits of electricity every day. So much so that we take it for granted that whenever we plug our gadgets into the wall socket, the power will be there. While most people give little thought to where electricity comes from, there are many different ways to generate electricity – including coal, oil, gas, hydroelectric, nuclear, and solar. Each option inherits certain advantages that merit consideration whenever there is a need for a new power plant. Nuclear-generated electricity is unique in that it inherently addresses many of the shortcomings of the other means for power generation. The use of nuclear power provides answers for many problems in the areas of the environment, safety, economics, reliability, sustainability, and even waste.

1.3 Nuclear Power Plants

Right now, nuclear energy provides about 20% of the US electricity, a little bit less of the world's electricity. That works out to about 7% of total energy we consume. There is a lot of opportunity for total energy fraction to go up, because nuclear energy can be used to produce transportation fuels. We can use it to produce hydrogen. We can use the heat to help with biofuel processing.

Nuclear-generated electricity is not just produced in the United States. Most developed countries worldwide have nuclear power plants generating electricity for their citizens. Furthermore, nuclear power generation continues to grow annually. With concerns over the environmental effects of global warming and pollution from gases emitted from coal-fired plants, the demand for nuclear power is projected to continue to increase a great deal in the next decades.

Currently, 30 countries worldwide are operating 437 nuclear reactors for electricity generation, and 67 new nuclear plants are under construction in 14 countries. Included in this number are 100 plants operating in 31 states.

While the United States can boast about having the most nuclear power plants, electrical power from these plants provides less than 20% of all power supplied in the United States. Other countries are much more dependent on nuclear than the United States. The next figure ranks the per capita supply of nuclear power for the top ten nuclear power-generating countries. Currently, nuclear energy represents about 77% of total electricity production in France, 54% in Slovakia, 54% in Belgium, 47% in Ukraine, 43% in Hungary, 42% in Slovenia, 40% in Switzerland, 40% in Sweden, 35% Korea Republic, and 33% in Armenia.

1.4 Cost of Electricity from New Nuclear Power Plant Stations

Current discussions about possibilities to mitigate the effects of global warming have also opened discussions about a potential revival of nuclear power. In this context, it is often argued with very low cost of electricity from nuclear power plants. This seems to be one of the strongest arguments in favor of atomic energy. To determine the future cost of electricity from nuclear power, the cost from currently operating power stations is considered. However, this is not correct.

In the above, we discuss about building new nuclear power stations; the cost for electricity from new and not from already existing nuclear power stations should be taken into account. This makes a huge difference as we will see further below. As a matter of fact, it is nearly impossible to estimate the cost of building new nuclear power stations. This is mainly a consequence of missing national and international safety standards. It is not clear which safety measures will have to be applied, and as a consequence, the investment costs can barely be estimated. Figure 1.2 is showing structure of a typical nuclear power plant from outside.

Outside of the United States, Finland is the only country in Europe where a nuclear power plant is currently being built. In this situation, the best possible practice is to use the costs for the plant in Finland for cost comparisons with other technologies.

1.4.1 Pros and Cons of New Nuclear Power Plants

As a result of the current discussion on how further global warming could be prevented or at least mitigated, the revival of nuclear power seems to be in everybody's – or at least in many politicians – mind. It is interesting to see that in many suggestions to mitigate global warming, the focus is put on the advantages of

Fig. 1.2 A typical structure view of nuclear power plant

nuclear power generation, and its disadvantages are rarely mentioned. With next generation nuclear plant (NGNP) known as GEN-IV, any disadvantages are playing very low key anyway. Bear in your mind that there is no perfect energy source. Each and every one has its own advantages and compromises.

Environmentally, nuclear power is once again considered a prominent alternative, despite the disregard it was met with in the 1970s. This is because it's now being touted as a more environmentally beneficial solution since it emits far fewer greenhouse gases during electricity generation than coal or other traditional power plants.

The environmental impact of any power generation station can be measured by quantifying the burden of fuel delivery, emissions of by-products and wastes, and the potential impact on the lives (human or otherwise) of those living nearby.

It is widely accepted as a somewhat dangerous, potentially problematic, but manageable source of generating electricity. Radiation isn't easily dealt with, especially in nuclear waste and maintenance materials, and expensive solutions are needed to contain, control, and shield both people and the environment from its harm.

In contrast to fossil fuel plants (coal, oil, and gas), nuclear power plants do not produce any carbon dioxide or sulfur emissions, which are major contributors to the greenhouse effect and acid rain, respectively. According to the Nuclear Energy Institute, US nuclear power plants prevent 5.1 million tons of sulfur dioxide, 2.4 million tons of nitrogen oxide, and 164 million metric tons of carbon from entering the Earth's atmosphere each year [2].