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Economic goals and requirements for competitive fusion energy

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Abstract

Future economic competitiveness, coupled to and constrained by environmental and safety characteristics, continues to provide a central strategic motivation and concern for fusion research. Attention must also be paid to the evolving cost projections of future fusion competitors, with appropriate consideration of externalized impacts, insofar as they establish the eventual market-penetration context and also influence the near-term funding climate for fusion R&D. With concept optimization and selection in mind, tradeoffs among system power density, recirculating power, plant availability (reflecting both forced and planned outages), complexity, and structural materials and coolant choices are best monitored and resolved in the context of their impacts on capital and operating costs, which, together with low fuel costs and financial assumptions, determine the projected life-cycle product cost of fusion. Considerations deriving from deregulation and privatization are elucidated, as are possible implications of modern investment-analysis methods. © 1998 Elsevier Science S.A. All rights reserved.

1. Introduction

As part of a general consideration of future energy issues [1], the rationale and methodology of cost projections for magnetic-fusion-energy central-station electric power plants have been considered for both the tokamak Demo [2] and the corresponding commercial power plant [3]. Changing market and regulatory conditions, particularly in the US, prompt fundamental reconsideration of what constitutes a competitive future energy-source technology and has implications for the direction and emphasis of appropriate near-term research and development programs, for fusion and other advanced generation systems. With fusion-concept optimization and selection in mind [4,5], tradeoffs among system power density, recirculating power, plant availability (reflecting both forced and planned outages), technical and operational complexity, and structural-materials and coolant choices are best monitored and resolved in the context of their impacts on capital and operating costs, which, together with (typically) low fusion fuel costs and exogenous financial assumptions, determine the product cost [e.g. cost of electricity (COE)].

The cost of electricity (COE) estimate at the busbar (neglecting transmission and distribution cost components of the retail price) combines the total cost estimate with reference economic groundrules to yield

$$\mathrm{COE} = \frac{C_{\mathrm{AC}} + (C_{\mathrm{O\&M}} + C_{\mathrm{SCR}} + C_{\mathrm{F}})(1+y)^{\mathrm{Y}}}{8760\ P_{\mathrm{E}} p_{\mathrm{f}}} + C_{\mathrm{D}} \quad (1)$$

where C_{AC} (M\$ year^{-1}) $= TCC \times FCR$ is the Annual Capital Cost (the product of the Total Capital Cost and the Fixed Charge Rate) and P_{E}

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(MW) is the net electrical output power, i.e. the Design Electrical Rating (DER). Annual operation and maintenance (O&M) costs, $C_{O\&M}$, are dominated by personnel costs, and are estimated by analogy to fission experience [6]. Annual scheduled-component replacement (SCR) costs, C_{SCR}, include the changeout of first-wall, divertor, and blanket systems with service lifetimes subject to neutron-fluence limits (e.g. ~12 MW year m^2). Annual fusion fuel costs, C_F, are negligible, except for (lunar) ^{3}He. The annualized value of decommissioning cost, C_D, is ~1 mill kWh^{-1}. Funds to be spent at end-of-life for decommissioning are accumulated over the first 30 years (analysis life) in an external sinking fund [7]. An explicit term for R&D cost, $C_{R\&D}$, could be included, as well, but assuming such costs can be effectively ammortized over a number of plants, it is dropped here, consistent with traditional practice. Also, no explicit account is made here for capital additions (or 'major exceptional maintenance' [6], e.g. the replacement of steam generators), which can be significant. The general inflation rate is y (i.e. 0% year^{-1} for constant-dollar evaluations and assumed to be 5% year^{-1} for nominal-dollar evaluations). For a reference construction spending profile [8], interest during construction charges are calculated for the construction lead time, τ_c = Y (assumed to be 6 years for fusion). Level of Safety Assurance (LSA) cost credits suggest possible savings as a result of materials and design choices incorporating passive-safety features.

2. The competition

Attention must be paid to the evolving cost projections of future fusion competitors, with appropriate consideration of externalized impacts, insofar as they establish the eventual market-penetration context and also influence the near-term funding climate for fusion R&D. Detailed international data summaries are available [9] for currently available options. To facilitate international comparisons, common discount rates are invoked, unrepresentative of actual experience. Other studies [10] take into account national financial factors and scenarios. Some salient parameters are summarized in Table 1.

2.1. Fossil

Steam coal (SC) and natural gas (NG) fuel-cost projections for the US, neglecting regional variations, are summarized in Fig. 1. The near-term picture favors the use of natural gas, particularly in small units, as the lowest cost option for incremental capacity, although displacement by coal is projected after ~2010. Near-term NG costs were thought [12] to be growing at a rate near 2% year^{-1}, but the most recent [14,22] extrapolations suggest less growth and even a decline in price. The situation for coal is similar. Of course, even these medium-range projections are uncertain and must be used cautiously. Technology improvements addressing efficiency and emissions issues are being pursued [23]. As a matter of public policy, emissions taxes could be imposed to discourage the emission of greenhouse gases (e.g. CO_2), thus internalizing this social cost. Carbon-tax rates of 5 \$ ton^{-1} CO_2 (18 \$ ton^{-1} carbon) are assumed in the near-term projections of Ref. [24]. For the nominal heat rate (Btu/kWh) values of 7520 for NG and 10160 for coal, the 1995 fuel-cost contributions to fossil COEs are 16.5 and 13.4 mill kWh^{-1}, respectively.

2.2. Fission

A revival of fission in the US depends upon a revival of public acceptance and a solution to the waste (particularly spent fuel) disposal issue, and, ultimately, the need for reprocessing and plutonium recycle. The cost projections of Ref. [12] and anticipated results from the Electric Power Research Institute (EPRI) consideration of passively-safe Advanced Light Water Reactors (ALWR) suggest desired COE values a decade hence in the range 45–55 mill kWh^{-1}, with a target COE below that of future nonnuclear competitors to offset the 'higher capital investment risk associated with nuclear plant utilization' [24]. The cancellation of the General Electric (GE) development of the 670-MW Simplified Boiling Water Reactor (SBWR) was attributed to delays in regulatory approval and the absence of an competitive niche [13]. GE will concentrate in-

Table 1
Some baseload power-plant candidates

Plant type	P_f	τ_c (years)	Size (MW)	COE (mill kWh^{-1})[a]
Fission				
POOR-ME[b]	0.65	10	1100	100
POOR-BE[c]	0.75	8	1100	57
IPWR[d]	0.75	6	1100	49
APWR[e]	0.75	6	550	61
APWR[e]	0.75	6	2×550	52
ELWR[f]	0.80	6	1200	45–51
ALWR[g]	0.80	5	600	46–55
ALMA[h]	0.80	5	9×165	43–50
SBWR[i]	0.80	(4)	670	Ref. [13]
Fossil				
Coal [10]	0.75	5	550	67
		5	2×550	62
Coal [12]	0.80	3.5	2×600	52–69
Coal [14]				46, 39
NG [12]	0.80	3	P2×600	61–116
NG [14]				39, 35
Renewables				
Wind [15]	0.25		200	→50
Fusion				
MFE:				
ARIES-RS [16]	0.76	6	1000	82
SPPS-MHH [17]	0.76	6	1000	80
TITAN [18]	0.76	6	970	(53)[j]
IFE				
HYLIFE-II [19]	0.85	6	1000	56

[a] Adjusted to 1995 (constant-dollar) using US Gross Domestic Product (GDP) implicit price deflator (IPD) [11].
[b] Pressurized Water Reactor-Median Experience, cf. Ref. [10], for 2000.
[c] Pressurized Water Reactor-Better Experience, cf. Ref. [10], for 2000.
[d] Improved Pressurized Water Reactor, cf. Ref. [10], for 2000.
[e] Advanced Pressurized Water Reactor, cf. Ref. [10], for 2000.
[f] Evolutionary Light Water Reactor, cf. Ref. [12], for 2030.
[g] Advanced Light Water Reactor, cf. Ref. [12], for 2030.
[h] Advanced Liquid Metal Reactor, cf. Ref. [12], for 2030.
[i] Simplified Boiling Water Reactor, cf. Ref. [13].
[j] cf. Ref. [18]. Reestimate using modern groundrules required.

stead on larger versions [25,26]. The US construction pipeline is nearly empty, but improvements in plant operations, particularly availability, are encouraging [27,28].

There is serious contemplation of plant sizes in excess of 1500 MW (net) consistent with presumed economies of scale [29,30]. Projected (at an unspecified date) COE values for a conceptual European Pressurized Water Reactor (EPWR) are 44–55 mill kWh^{-1} and for a European Fast Reactor (EFR) are 46–53 mill kWh^{-1} [31].

2.3. Renewables

Renewable sources [32] of electricity include solar thermal, solar photovoltaic (PV), windpower, and biomass. While the present economic performance of these approaches is mixed [33], future cost targets range from 35–65 mill kWh^{-1}, assuming manufacturing cost reductions resulting from mass production and exploitation of favorable sites [14,15,34]. Renewables may address peak loads, as opposed to baseload requirements, absent a suitable energy-storage scheme.

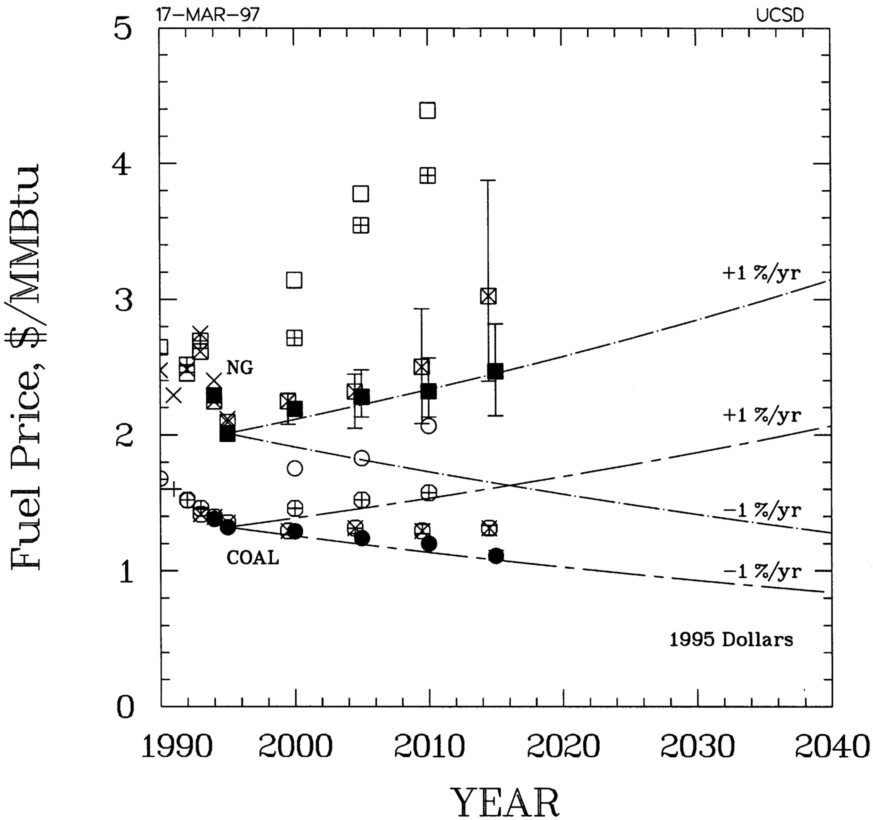

Fig. 1. Fuel cost projections for natural gas (NG) and coal from a series of recent US Energy Information Administration (EIA) estimates for 1994 [20] (open points), 1995 [21] and 1996 [22] (partially filled points), and 1997 [14] (solid points), indicating the progressive softening of these fossil-fuel prices. The extrapolation curves reflecting the more recent escalation rates are lower than those used in Ref. [12] to represent the then-available projections, necessitating an updated comparison and increasing the competitive pressure on fusion. Extension of the projections beyond 2015 is a convenience for purposes of Fig. 2 below (Note: 1 MMBtu $\simeq$ 1.055 GJ).

2.4. COE projections

The results of Ref. [12] are generalized in Fig. 2 to set the market context for electrical production in the ~2025 time-frame for Demo and the ~2040 time-frame for early commercial fusion power plants. The identification of specific introduction dates is no longer explicit under the revised US strategic plan for fusion [36]. Included are constant-dollar busbar Cost of Electricity [COE (mill kWh^{-1})] projections for fission, including an evolutionary light water reactor (ELWR) and a passively-safe advanced light water reactor (ALWR), an advanced pulverized-coal (PC) plant, and a combined cycle combustion turbine (CCCT) burning natural gas. The fission cost projections assume a favorable regulatory and licensing climate and a solution to the radioactive waste disposal issue, absent which, no additional fission capacity is likely [21]. The coal and natural gas projections, neglecting regional variations, are shown for a range of fuel-cost escalation rates over and above the general inflation rate (5% $year^{-1}$), consistent with eventual depletion. The near-term picture favors the use of natural gas, particularly in small units as the lowest cost option for incremental capacity, although displacement by coal is projected after ~2010. The EPRI projections [24] for ca. 2005, designated steam-coal (SC, open circle) and natu-

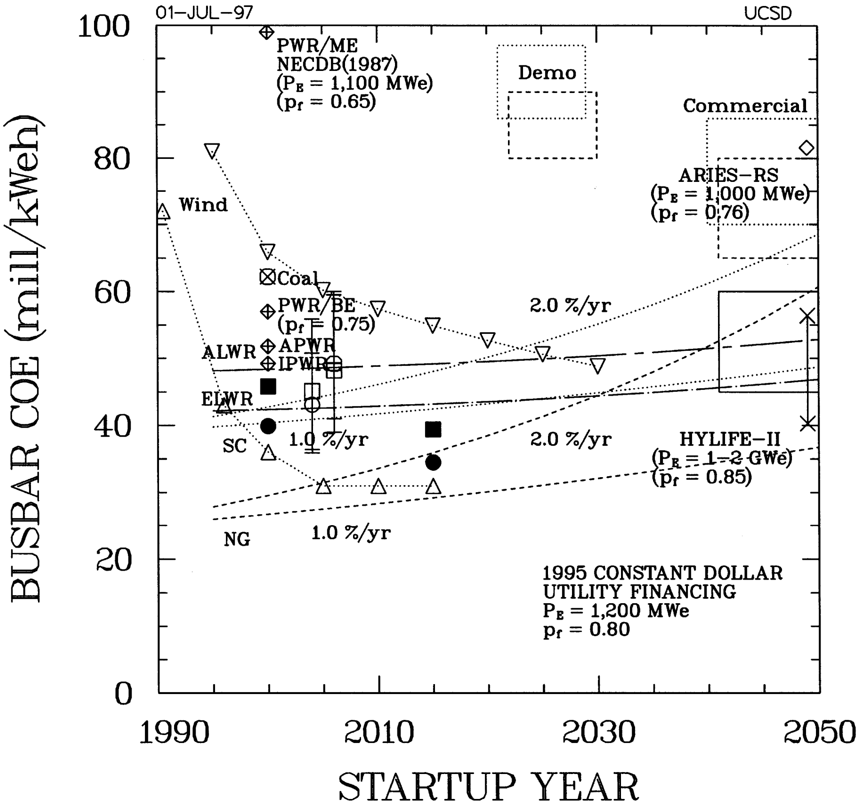

Fig. 2. Busbar Cost of Electricity [COE (mill kWh^{-1})] projections, setting the market-penetration context for fusion, based on Refs. [10,12]. EPRI characterizations [24] for steam-coal (SC, open circle) and combined-cycle natural gas (NG, open square) with and without a nominal carbon tax are shown near 2005. The EIA projections [14] to 2015 (corresponding solid points) reflect some improvements in the underlying plant efficiency and include projections for wind (△) considerably lower than those (▽) of Ref. [15]. The fossil (SC, dotted curves) and (NG, dashed curves) projections reflect the indicated range of fuel cost escalations and a plant capacity factor, $p_f = 0.80$, and, like the fission curves for an evolutionary light water reactor (ELWR) and a passively-safe, advanced light water reactor (ALWR), take $P_E = 1200$ MW. Target windows for the Starlite Demo and subsequent commercial power plants (e.g. tenth-of-a-kind ARIES-RS tokamak [35], represented by ◇) are indicated by the dashed boxes, with (dotted) and without (dashed) adjustment from 1992 to 1995 dollars, with the upper boundary representing the 'requirement' and the lower boundary representing the 'goal'. The IFE HYLIFE-II design [19] meets the new (lower) commercial target, denoted by the solid box. The timing of these target boxes is no longer explicit in the new US strategy [36].

ral gas (NG, open square) are included, together with the (higher) corresponding cases assuming an imposed carbon tax.

3. Changing US Market

The US electrical sector is only now emerging from a 25-year period of excess capacity [11,37], such that it is sensible to contemplate acquisition of new baseload plants. The US electrical sector is undergoing a transition from a situation dominated by vertically integrated, captive-market, regulated retail-monopoly utilities to a deintegrated, competitive-market, less-regulated landscape, under which electricity is becoming a commodity. Traditionally integrated functions of generation, transmission, distribution, and ancillary services [38] are becoming unbundled. The implications of the emerging landscape are not well understood, but restructured utilities and independent power producers are expected to be reluctant to take on capital-intensive central-station baseload power plants of any technology, as long as the present era of cheap NG persists. As the US electrical energy sector evolves from its traditional utility base, certain financial factors with adverse implications for capital-intensive options, such as fusion, come into play. For example, the typical financial portfolio of nonutility generators (NUGs) and Independent Power Producers (IPPs) results in higher fixed charge rates (FCRs) for them, which would discourage their choice of any capital-intensive generating option, as indicated in Table 2. With different typical capitalization fractions, the industrial and highly leveraged IPPs can expect higher values of interest during construction and higher fixed charged rates (FCR). Thus, the ratio of total capital cost (TCC) and corresponding incremental cost of electricity (COE) for a typical tokamak power plant might be prohibitively high, narrowing the potential customer base.

Because of currently slow demand growth in the US relative to the 1970s, baseload capacity additions are minimal. It is not clear that the operation of deregulated energy markets is entirely consistent with safety and environmental protection [39], not to mention such public-policy principles as sustainability and intergenerational equity [40]. Also, market interventions, in the form of tax incentives or emissions penalties, are not precluded and may persist. The changing market situations in Japan, Europe, and elsewhere may follow different paths, it should be noted.

4. New assumptions and methods

It is appropriate to re-examine the issue of plant size in order to take advantage of economies of scale [41], provided that the impact on plant factor is properly addressed. It can be anticipated that some engineering problems (e.g. high surface heat loads on plasma-facing components) will inhibit the feasibility of large MFE fusion plants at some point. It is also appropriate to revisit the 'learning-curve' cost credits in the interest of consistency [42]. A general review of the direct costs can now be grounded in ITER information [43].

Traditional costing methods [7,44] based on the Revenue Requirements Method (RRM), while suitable to the regulated regime, may prove inappropriate to the future scene. Under the traditional cost-of-service model, retail rates are set (usually by state-level public service commissions), to compensate for expenses plus an allowed rate

Table 2
Economic parameters[a]

Parameter	Util.	Ind[b]	H-L[c]
Capitalization fraction[d]			
Debt (bond)	0.50	0.30	0.70
Preferred stock	0.10		
Common equity	0.40	0.70	0.30
Return on capitalization (/year)			
Debt interest	0.097	0.097	0.130
Preferred dividend	0.090		
Common equity return	0.140	0.170	0.220
Average cost of money (/year)	0.1135	0.1481	0.1570
Real[e] average cost of money (/year)	0.0605	0.0934	0.1019
Effective[f] cost of money (/year)	0.0957	0.1374	0.1237
Real[d] effective cost of money (/year)	0.0435	0.0832	0.0702
Interest during constr.[g], f_{IDC}			
Then-current (nominal)-dollar	0.3178	0.4300	0.4601
Constant-dollar	0.1652[h]	0.2642	0.2909
Fixed Charge Rate (FCR)			
Then-current (nominal)-dollar	0.1637	0.2202	0.2011
Constant-dollar	0.0965[h]	0.1436	0.1273
TCC/TCC (Util.)[i]	1.00	1.09	1.11
COE/COE (Util.)[j]	1.00	1.50	1.37

[a] Typical US assumptions with $y = 0.05$, cf. Ref. [7].
[b] Industrial (conservatively financed) IPP.
[c] Highly-leveraged IPP.
[d] US Utility recent history cf., Ref. [37].
[e] Inflation-adjusted discount rate.
[f] Tax-adjusted discount rate.
[g] Assuming 6-year construction lead time.
[h] For fission and fusion, cf. Refs. [35,12], as used in Eq. (1). Compare with 0.1655 (nominal) and 0.0976 (constant) for fossil.
[i] Typical tokamak case, cf. Ref. [35], with TCC (Util.) $\simeq$ 4.2 B$.
[j] Typical tokamak case, cf. Ref. [35], with COE (Util.) $\simeq$ 75 mill kWh^{-1}.

of return applied to the rate base. Alternative schemes of performance-based pricing [45], for example, the target capacity factor (TCF) approach, can affect power-producer operations and capacity-addition choices in significant way, rewarding efficient operation and discouraging complex, unreliable options, and generally forcing operation at economic margins.

The traditional work-product, a conceptual point-design, may have to be demphasized in favor of a broader characterization of the 'design window', in the sense of Response Surface Methodologies (RSM) [46], extending available parametric efforts [47]. More emphasis will have to be placed on displaying the evolving uncertainty distribution, of which the traditional COE value is (only) the expected value. To the extent that the major attributes of the generation options cannot be internalized into the COE metric, a multiattribute quantification [48] is appropriate. The issue of the robustness of design points can also be addressed more rigorously [49,50].

5. Conclusions

A vigorous cost competition can be anticipated for future sources of electrical power as deregulated markets come into being and as new technologies mature. Projected COE targets [60 mill kWh^{-1} ('required') and 45 mill kWh^{-1} ('goal')] account for alternatives to fusion likely to exist in the future, recognizing that fusion will enter an increasingly competitive marketplace. These proposed new targets are more demanding than those used in the Starlite study, in which the ARIES-RS conceptual design was developed. Thus, further improvements and innovation in the MFE designs should continue to be sought.

Prospects for the simultaneous achievement of unit overnight costs below 3000 \$ kW^{-1}, and plant capacity factors near 80%, which are consistent with a cost of electricity 'requirement' for fusion of 60 mill kWh^{-1} is difficult for leading (as presently understood) magnetic fusion power plant candidates. The fundamentals of power density, recirculating power, complexity act to the disadvantage of fusion and offset the negligible fusion fuel cost (excepting lunar ^3He). Allowance for the payment of a 'premium' in order to obtain environmental or other advantages relative to the perceived competition can be entertained only so far. For magnetic fusion to be environmentally and economically competitive, concept improvements and innovations are essential.

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