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Disequilibrium, 'lock-in' and potential double dividends: The case of distributed combined heat and power (DCHP)

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Abstract

This paper addresses the potential for so-called ‘double dividends’, a possibility still largely dismissed by economists and, consequently by policy-makers. To come to grips with this question, the paper begins with a discussion of the notion of competitive equilibrium. This is followed by a discussion of the link between disequilibrium and innovation, and the non-linear dynamics of competition between technologies with increasing returns, resulting in path-dependence. Increasing returns to adoption permit ‘lock-in’ of inferior technologies due to economies of scale and experience. However, in time, the initial advantage can be lost due to further innovation. This, in turn, is largely responsible for the existence of opportunities for ‘double dividends’. Double dividends can result when technological progress enables a technology that was originally ‘locked out’ to become competitive at a later time. The paper concludes with a detailed analysis of what is arguably the most important opportunity for double dividends in the US and world economy, namely overcoming the ‘lock-in’ of the monopoly electric power distribution system. This would encourage wider application of co-generation and/or decentralized combined heat and power (CHP) technology, with dramatic reductions in costs, carbon dioxide output and improved overall system reliability.

About the Author

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Robert U. Ayres

Competitive equilibrium: concept and reality

The intellectual background for this paper begins with the idea of economic equilibrium. It goes back at least to Adam Smith's first articulation of the idea of an ‘invisible hand’, which supposedly assures an efficient allocation of resources by ‘beneficent providence’ through the operation of a price mechanism in free competitive markets. This seminal idea was refined by Ricardo, Say, Walras, Jevons, Edgeworth, Wicksell, Pareto and others in the 19th century.

Walras postulated a unique competitive equilibrium, namely a set of prices such that supply would exactly balance demand in each market (i.e. for each good or service), including labor. Walras also postulated a kind of auction process, called tâtonnement, by means of which the equilibrium state would be reached spontaneously, assuming each market actor was always fully informed by a sort of super auctioneer about all transaction prices. Even though Walras was not able to prove this conjecture, it was widely accepted and had an enormous influence on subsequent developments in economic theory.

It was recognized long ago that one of the keys to the existence of a stable competitive equilibrium is the universality of a property known as declining marginal utility of consumption for all consumers and declining marginal productivity of capital for all producers. The general acceptance of these properties became known as the “marginal revolution” in economics, dating back to Jevons and Walras c. 1870. It has enabled mathematicians to study the properties of markets and to derive general theorems about their behavior.

The first mathematical proof-of-existence of an equilibrium (in the above sense) depends on some restrictive simplifying assumptions.[i] Among them are the following:

1) The supply side of a competitive equilibrium consists of a large number of small independent producers (no *monopolies* or *oligopolies*); the demand side consists of a number of small independent consumers. None of the producers or consumers is able to influence prices or aggregate production levels.

2) Every commodity or service in the economy is produced from labor or from other commodities and services produced by the economy and sold in the market. By implication, no resources are taken from the environment and the environment provides no unpriced services (such as waste disposal). In other words, the economy is *closed*, and prices are unaffected by anything outside the market. Moreover, the closed economy produces only **goods**; there are no 'bads' or *externalities*.

3) Each agent in the market is a perfectly rational utility maximizer. He is consciously aware of his own preferences and can instantaneously and consistently decide how he will re-allocate his income among all possible goods/service, given any change in market prices.

4) Each agent in the market is perfectly informed about the prices and characteristics of all products and services offered for sale at all times. If any change *were* to occur (e.g. the introduction of a new product), it is assumed that information about it is instantaneous and automatically available to all agents.

The most important theorems about competitive equilibrium are as follows: (1) all product markets, and labor markets, "clear" in the sense that supply and demand are perfectly balanced and (2) once an equilibrium state has been reached, no transaction can improve the position of one agent without hurting that of another or others. The first attribute — market clearing — makes the competitive equilibrium *efficient*: there are no wasted or unutilized resources, either of capital or labor. The second important attribute of competitive equilibrium is known as *Pareto optimality*. In game-theoretic terms we can say that, in a Pareto optimum state, all economic contests are, at best, "zero sum", meaning that the sum of all gains and losses add up to zero (or less).[ii]

The Pareto-optimal equilibrium state of an economy is, by definition, static. It is a state in which all agents in the system are as well-off as they can be, in the sense that no agent can improve its welfare/utility by voluntarily exchanging any goods or services with others. As a tool of analysis — a point of departure for theory — this concept is invaluable. It is, perhaps, the one area where truly rigorous analysis has been possible in economics, thereby differentiating economics from "softer" social sciences.

So much for the good news. The bad news is that the economy is never actually in equilibrium. For example, Joan Robinson remarks *"The concept of equilibrium is, of course, an indispensable tool of analysis … But to use the equilibrium concept, one has to keep it in its place, and its place is strictly in the preliminary stages of an analytical argument, not in the framing of hypotheses to be tested against the facts, for we know perfectly well that we shall not find facts in a state of equilibrium."* (Robinson 1962) p. 78. She goes on to note that *"Long run equilibrium is a slippery eel. Marshall evidently intended to mean by the long period a horizon which is always at a certain distance in the future, and this is a useful metaphor, but he slips into discussing a position of equilibrium which is shifted by the very process of approaching it … No one would deny that to speak of a tendency toward equilibrium that itself shifts the position towards which it is tending is a contradiction in terms …"* [Ibid p.79].

The only production or exchange that occurs in an equilibrium state will be production of services that are “consumed” as they are produced (e.g. food), or to replace goods that are physically used up or depreciated. In a Pareto optimum nobody wants to buy more than he/she buys now, if it means giving up leisure time by working more hours to earn more money. Nobody wants to exchange the goods he has to buy others at the prices offered. In short, everybody is satisfied with the *status quo*, by assumption.

The same problem arises on the supply side. In a competitive static equilibrium there are no competitive advantages from scale. There can be no ‘extraordinary’ profits (i.e. profits greater than required to replace depreciated capital). This is because there are — by assumption — no monopolies or oligopolies, so the cost of entry to any market is zero or negligible. Since all firms are assumed to have perfect information with regard to production possibilities, any firm that found an opportunity for making higher-than-average profits would immediately attract price-cutting competitors. Anyhow, no such opportunities for extraordinary profits could exist because each firm and sector has, by assumption, already selected the best available production technology for its product. In fact, competition among price-takers ensures that prices will inevitably fall to the marginal cost of production. Producers in a competitive equilibrium can expect to replace capital depreciation, but no more. Producers could never earn a return on equity capital sufficient to finance growth.

Here are some other facts that are inconsistent with static equilibrium:

Fact 1. Real markets do not always clear. Both backlogs and shortages occur from time to time. Unemployment is, of course, inconsistent with equilibrium in labor markets.

Fact 2. Businesses in the real world do not price uniformly on the basis of cost. Enormous price differences in different countries have been documented (even within Europe) for brand name products, such as cosmetics, drugs and vitamins, where cost differences are irrelevant.

Fact 3. Consumers in the real world do not insist on the lowest possible price, especially for domestic goods as compared to foreign imports. Americans once looked for the label “Made in USA” (which allegedly induced a Japanese exporter to locate itself in a town called Usa). Japanese consumers, in turn, willingly pay two to ten times world prices for commodities like rice, beef and fruit, as long as they are produced domestically.

Fact 4. Real firms often do not operate on or near the so-called *technology frontier* as they are assumed to do. There is ample evidence of this, some of which I note subsequently. (In fact, this is the source of many “double dividend” possibilities.)

Fact 5. Some technologies are ‘locked in’ by a combination of market power and institutional barriers (such as standards), while others — potentially superior — can be ‘locked out’ by the same

> mechanisms (Arthur 1994). The classic example in the literature is the QWERTY typewriter keyboard (David 1985). The British system of weights and measures has been locked in by the US and Britain, while the metric system has been locked out. Driving on the left (or the right) is another case in point. The most important example of lock-out today may be decentralized combined heat and power (DCHP), which has been effectively locked out by centralized electrical utilities with monopoly rights over a given territory. This case will be discussed later.

It is important to note that in a dynamic economy the initial advantage resulting from returns to adoption and 'lock in' may not be permanent. We consider that case later.

On the impossibility of growth-in-equilibrium

For reasons summarized above, the real economy is never in equilibrium. It certainly follows that the idea of *growth-in-equilibrium* inherently makes no sense. In a true equilibrium state there would be no better-than-average (or worse than average) investments, no growing (or declining) sectors, no variability of prices. The 'quasi-equilibrium' theories now being explored may accommodate some structural change, providing it is slow and gradual. In this sense, it is only an incremental improvement over previous theories of growth-in-equilibrium. There is no room in the theory, however, for significant departures from equilibrium. There is no room in the conceptual scheme for hyper-inflation, "oil shocks", stock market crashes or "bubbles", not to mention wars or natural catastrophes.

The second reason for rejecting growth-in-equilibrium models is that the mechanisms that drive economic growth, whether savings and investment, or technological innovation in pursuit of monopoly profits, are essentially non-equilibrium phenomena. On close examination it can be seen that the strength and effectiveness of these mechanisms is a function of the 'distance' of the system from an hypothetical equilibrium state. In the Pareto-optimal equilibrium state, nothing changes because all economic agents have already maximized their utility. They are all as well off as they can possibly make themselves through economic transactions. Why save and invest? Why innovate? The 'rainy day' explanation of savings is untenable: in a perfectly competitive market economy one simply buys insurance. Similarly, the 'monkey curiosity' explanation of scientific research and technological development is also untenable.

The classical explanation of savings and investment behavior[iii] is that consumers find it optimal to forego some current consumption in order to secure a higher level of consumption in the future through investment and consequent income growth. The tradeoff between current and future consumption is the *discount rate*, which is traditionally equal to the *interest rate* on savings. (If the interest rate were higher than the discount rate, people would increase their savings; and conversely). This argument was fully articulated in mathematical terms long ago (Ramsey 1928). Riskier investments should carry higher rates of return to compensate for the risk. But the incentive to invest actively (as opposed to putting money in the bank) is clearly higher in proportion to the difference between the expected rate of return and the bank interest rate. *This difference is also a measure of disequilibrium, since in the postulated equilibrium state it would vanish.*

In an equilibrium economy there would be no investment in R&D (formalized or not)? Walrasian equilibrium – with or without simple human curiosity – will not account for Bell Telephone Laboratories. Schumpeter’s explanation (the search for monopoly profits) is far more plausible (Schumpeter 1912). Mansfield has provided a wealth of empirical data to support this hypothesis (Mansfield and et al 1977). If the economy were truly in Walrasian equilibrium, either the opportunity to patent a new idea could not exist or — which is the same thing — it would be simultaneously available to all. Anyhow, monopoly profits are not possible by definition in a pure Walrasian model with perfect competition (no monopolistic price-makers). Thus, unequal distribution of intellectual property — knowledge, ideas, technology and skills — is another measure of disequilibrium and opportunity.[iv]

The ‘quasi-equilibrium’ picture emerging from the new theory of endogenous growth does reflect some of the necessary motivational factors driving savings and investment, including the possibility of earning monopoly profits from innovation. This is a step forward., but not nearly a big enough one.

To make the case that the real economy is not growing in equilibrium, nor is it very near equilibrium, it is simpler to point out some empirical facts about growth that are inconsistent with the notion of moving equilibrium:

Fact 1. The structure of the economy is changing over time. Some sectors are declining; others are growing. To take an obvious example, the coal, rail and shipbuilding industries are declining. The semiconductor, computer, telecom and biotechnology industries are growing. This kind of structural change would not occur on an equilibrium (*homothetic*) growth path.

Fact 2. Profit opportunities vary enormously from sector to sector. A study of the 100 biggest firms in the world in 1912 has shown that the 14 petroleum firms in the sample outperformed the S&P 500 index by a factor of 3.7 in market valuation (Hannah 1996). During the same period 5 electrical engineering firms outperformed the S&P by a factor of 2.7 (despite the laggard performance of Westinghouse); 10 chemical firms achieved a performance ratio of 2.4, and 18 ‘branded products’ firms managed a combined ratio of 1.3, just above average. Meanwhile iron & steel and heavy engineering (18 firms), mechanical engineering (14 firms), non-ferrous metals (10 firms), coal mining (7 firms) and textile and leather goods (4 firms) performed below average, with the last category performing at only 0.1 (10%) of the average level [*ibid*]. It is scarcely necessary to note that the laggard sectors were already mature in 1912, while the best performers were all still relatively youthful in terms of the product life cycle.[v]

Fact 3. Growth rates vary enormously between countries and periods. This should not be the case given the conditions postulated for a competitive equilibrium. Thus, even the "endogenous" version of neo-classical growth theory can scarcely hope to explain the wide variations between countries except in terms of degrees of failure to satisfy the requirements of the theory (e.g. lack of 'openness').

Fact 4. If the market were in equilibrium it would have to be 'efficient'(in the economic sense). If the market for goods and services were truly efficient the market for stocks and shares would surely be efficient also. In this case, the market would act as an instantaneous information processor, such that all facts bearing on the price of a stock would automatically and instantaneously be incorporated in its price. In this case, no simpler model of the stock-market (i.e. a set of investment rules, based on public information) could possibly perform as well as the market itself over a significant interval. In other words, all investment models would perform necessarily worse than the index averages. In fact, most do, but there are obvious exceptions such as Fidelity Magellan, and Warren Buffet's Berkshire Hathaway.

Given the realities, one can only conclude that markets are not particularly efficient, and that firms need not necessarily operate on (or near) the efficiency frontier in order to survive for long periods. Indeed, economic growth is a process that is fundamentally dependent on disequilibrium.

Path-dependence, 'lock-in' (and 'lock-out')

An important aspect of the technology selection process that follows a breakthrough, in practice, is that one candidate configuration is selected and often 'locked in' before all (or even many) of the possible combinations has been tested. The mechanism for this is known as *returns to adoption,* which also includes static economies of scale and dynamic economies of learning-by-doing and accumulating experience. Economies of scale are well understood by every manufacturer, although their contribution to path-dependence and 'lock-in' may not be so well understood.

Learning-by-doing (which can be 'embodied' in the design of capital equipment as well as workers and organizations) is one of the dynamic mechanisms to increase labor productivity and cut production costs. An early, and still influential, article on this process appeared in the economics literature four decades ago (Arrow 1962). Other noted a complementary process of 'learning-by-using' (Rosenberg 1982). These two processes, together with economies of scale in a growing economy, would seem to predict a smooth and moderately predictable labor productivity gains. At the macro-level such gains are normally just assumed. But in some attempts to endogenize technical change, they have been attributed to 'experience' e.g.(Verdoorn 1951), (Verdoorn 1956), (Rowthorn 1975), (Rayment 1981), (McCombie 1982).[vi]

Increasing returns as a generic mechanism have been explored more recently (Arthur 1994). In particular, *returns to adoption* are much less familiar. However some network communications systems (notably telephones and the Internet) are fairly obvious examples: the more nodes in the network, the more valuable the service is to each subscriber. However, there are other less obvious but no less important examples. The more Fords are in service, the easier it will be to find spare parts and service for a Ford. At all events, when a new technological possibility emerges, the first two or three combinations that 'work' reasonably well tend to lock out the others. Lock-out/lock-in is another way of saying that once a technology has become established, it is extremely difficult to displace – thanks to various advantages accruing to scale, experience or network linkages – even if an alternative emerges that is intrinsically superior but not fully developed.

Favorite examples of this phenomenon include the QWERTY keyboard (David 1985), the English system of weights and measures, the boiling water and pressurized water nuclear reactors developed for the US Navy in the early 1950s (Cowan 1989), and the Microsoft 'Windows' operating system for PCs. At the aggregate national level, a number of studies have indicated that, if the US economic system operated on a 'least cost' basis (i.e. by assuming the most efficient solutions were utilized everywhere), energy consumption and carbon emissions would both be reduced by something like 20% and costs would also be lower by a similar amount (Sant 1979; Sant and Carhart 1981; Morris et al. 1990; Berndt, Manove, and Wood 1981; Carhart 1979; Lovins and Lovins 1981; Lovins et al. 1981; Lovins and Lovins 1991; Casten and Collins 2002, 2003). In effect, the argument is that the economy has been 'locked in' to sub-optimal patterns by some combination of positive returns to scale, and inappropriate or obsolete regulations.[vii] The question arises: when (if ever) does it make sense to 'unlock' the locked-in technology?

To be sure, many economists deny that an alternative to the existing system would in fact cut costs, usually by introducing the notion of 'hidden costs' of change (for instance, see (Liebowitz and Margolis 1995)). An established technology cannot be displaced without also displacing a host of associated technologies and investments. But the undeniable existence of some (hidden and unquantifiable) costs of moving from one local minimum to another in a multi-equilibria system does not contradict the possibility that another minimum may be significantly lower than the one we currently occupy.

What about double dividends?

In the computable general equilibrium (CGE) and similar models, which assume perpetual optimality, there may be multiple optima but there is no allowance for the possibility of 'phase transitions' between optima. In simpler language there is no allowance for overlooked opportunities for environmental improvements or reduced resource (i.e. energy) consumption at negative costs, or even at a profit (the 'double dividend' or 'free lunch'). According to standard theory, such a situation cannot arise in a competitive equilibrium because every agent has already exploited all possible opportunities for improving its welfare. This what competitive equilibrium means.

A well-known example is the controversy over the so-called 'Porter hypothesis'(Porter 1991; Porter and van der Linde 1995). Porter suggested that countries that invested in environmental protection might also reap commercial advantage by gaining experience in efficient ‘clean’ manufacturing and exporting pollution treatment technologies. The hypothesis has spawned a large literature, largely (but not entirely) devoted to tax policy. Neoclassical economists convinced of the validity of the optimal choice axiom, have generally been skeptical (Goulder 1994; Palmer, Oates, and Portney 1995; Simpson and Bradford 1996).

When a non-economist suggests that such possibilities do exist in reality, the stock rejoinder is “if such an opportunity did exist, some entrepreneur would have found it and exploited it”. If an apparent opportunity is not exploited the standard explanation, as noted above, is ‘hidden costs’ often within the organization (Gabel and Sinclair-Desgagne 1998). This satisfies most economists but few engineers or scientists. Be that as it may, in neo-classical economic theory the possibility of significant double dividends is usually assumed to be negligible.

Examples of studies suggesting the existence of unexploited opportunities for high returns, indicating disequilibrium, have nevertheless been cited extensively (Lovins et al. 1981; Ayres 1994; von Weizsaecker, Lovins, and Lovins 1998; Lovins 1996). One unfamiliar example but extremely convincing is worth repeating here. It comes from the experience of the Louisiana Division of Dow Chemical Co. in the U.S. In 1981 an “energy contest” was initiated, with a simple objective: to identify capital projects costing less than $200,000 with payback times of less than 1 year (Nelson 1989). In its first full year (1982), 38 projects were submitted, of which 27 were selected for funding. Total investment was $1.7 million and the 27 projects yielded an average ROI of 173%. (That is, the payback time was only about 7 months). Since 1982, the contest has continued, with an increased number of projects funded each year. The ROI cutoff was reduced year-by year to 30% in 1987, and the maximum capital investment was gradually increased. For 1993 140 projects were funded for $9.1 million. *Table I* below summarizes the results of the Dow experience.

It is interesting to note that, although the number of funded projects increased each year, there was (through 1993) no evidence of saturation. Numerous profitable opportunities for saving energy, with payback times well below one year, still existed even after the program had been in existence for 12 years. Almost unbelievably, the average ROI of the funded projects did not decrease, as it would have done if the first projects had been exceptional examples of ‘low hanging fruit’. On the contrary, the average ROI increased. For the years 1991 and 1992 the ROIs were 309% and 305%, with a slight decline to 298% in 1993. Over the 12 years since the contest began, the average post-audit ROI on 575 audited projects was 204% and total audited savings are over $100 million *per year*.

Table I: Summary of Dow Energy Contest Results – All Projects

	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Winning Projects	27	32	38	59	60	90	94	64	115	108	109	140
Capital, $MM	1.7	2.2	4.0	7.1	7.1	10.6	9.3	7.5	13.1	8.6	6.4	9.1
Average ROI (%)	173	340	208	124	106	97	182	470	122	309	305	298
ROI Cut-Off (%)	100	100	100	50	40	30	30	30	30	30	50	50
Savings, $M/yr												
Fuel Gas(a)	2970	7650	6903	7533	7136	5530	4171	3050	5113	2109	5167	4586
Capacity	83	-63	1506	2498	798	3747	13368	32735	8656	17909	11645	20311
Maintenance	10	45	-59	187	357	2206	583	1121	1675	2358	2947	2756
Miscellaneous						19	-98	154	2130	5270	518	788
Total Savings	3063	7632	8350	10218	8291	11502	18024	37060	17575	27647	20277	28440

Source: (Nelson 1993): Tables 4 and 6

On the average, all energy contest projects have paid for themselves in 6 months, with a drop to 4 months in the last 3 years! One would have to suspect that the program could still be expanded many-fold before returns fell to the 30% ROI threshold. Furthermore, it is important to emphasize that these opportunities existed even in a sophisticated and cost conscious firm at relatively low U.S. energy prices. Should taxes or a new energy crisis force U.S. prices higher (i.e. toward world levels), the number of such opportunities would almost certainly be multiplied further.

Total savings over the twelve years of the contest have not been published but must surely be of the order of 1 billion dollars. This was money that went directly to profits: i.e. the bottom line. It undoubtedly added billions to the market value of Dow stock, and the CEO’s bonus. Sad to report, the initiator and ‘champion’ of the contest, Mr. Kenneth Nelson, received no reward whatsoever for his efforts on behalf of the company. He left the firm in 1994. He was not promoted to high rank. He was never given significant recognition for his outstanding services. Senior officials in other parts of the company did not even know of his accomplishments.[viii] As far as I am aware, no other division of Dow has attempted to duplicate Nelson's accomplishment, nor has it been imitated elsewhere.

The Dow case has strong implications for fundamental economic assumptions about firms. The standard theory assumes that firms operate on or very near the so-called efficiency 'frontier'. Obviously Dow did not, and does not. Yet Dow is obviously successful (indeed, it is greatly admired in some quarters) and it is certainly competitive, by most measures. How can this be?

I do not have inside knowledge as to why Dow (and its competitors) did not follow up on Nelson's profitable (but radical) idea. I can only guess. But, for whatever it is worth, I guess that one of the reasons was, basically, that Nelson's operation could not succeed without Nelson himself, or someone like him, who was prepared to risk his career on an idea. Success required, among other things, the empowerment of low-level engineers to make capital allocation decisions, thus reducing the authority of higher level managers. This creates a conflict of interest, since company culture is invariably focused on *growth*. There are rewards to managers for growing. There are no rewards, at the lower levels of the management hierarchy at least, for finding savings in existing operations, except by means of layoffs. There is no penalty for *not* finding savings (unless the company is in dire straits). There are serious penalties for failure, however. Careers die on the vine. Indeed, even success can be dangerous: any executive who suddenly discovers a way to save a lot of money *from existing operations* is sure to embarrass the executives who preceded him in the job. One of those preceding executives is very likely to be the boss (or a higher level boss). It does not pay to embarrass the boss.

Received neo-classical economic theory offers no convincing explanation for the Dow example, or others that have been cited. As already mentioned, mainstream theorists tend to insist that such possibilities are really exceptional. My own explanation is simpler: the mature industries are all oligopolies. Oligopolies resist change. Risk-taking is strongly discouraged in large firms. Successful innovation is not consistently rewarded. Credit for successful innovation is routinely claimed by hierarchical superiors. But failure is likely to be punished by career derailment, if not worse. Oligopolies make a show of competing, but they are not really structured to compete effectively.

In short, the idea of competitive equilibrium is seductive, but it does not describe the real world. CGE models, which depend on the idea of growth-in-equilibrium have very little predictive power. There are some questions for which such models can provide useful insights, for instance proposed changes in tax policy. But the problem of predicting long-range economic growth — especially with exogenous technological change — is certainly not one of them. There is also no room in the equilibrium picture for radical innovation, "free lunches", or "double dividends" whereby a firm can reduce effluent emissions and environmental damage by cutting waste and reducing inputs, while at the same time making bigger profits than before. These possibilities are simply assumed away by the model structure, although they unquestionably do exist.

The case cited above exemplifies the existence of unexploited opportunities, even in competitive firms. A far more important example is discussed below;

The DCHP case

Perhaps the most important example of a double – actually triple – dividend that has evidently been 'locked out' is the low rate of utilization of decentralized co-generation or decentralized combined heat and power (DCHP). In simple words, the idea encompasses two approaches. The first is to utilize low temperature heat from steam-electric power generators, that would normally be dissipated in air or cooling water, for residential or commercial space heating or water heating. This displaces boiler fuel that would otherwise be used. The second approach is to utilize high temperature waste heat or pressure from petroleum refineries, blast furnaces and the like to generate electric power that can be utilized on the same site or nearby.

The logic of using otherwise wasted low temperature heat from power generation to replace boiler fuel for heating is overwhelming. *Figure 1* illustrates the benefits schematically: to produce 35 units of electric power and 50 units of heat via CHP (co-generation) requires of the order of 100 units of fuel exergy, as compared to 189 units if the electricity and heat are provided separately. The overall losses in this example are reduced from 104 units to only 15 units, an enormous gain. Fuel inputs are reduced by 89 units out of 189, nearly a factor of two. The first strategy has been widely adopted, mainly in Scandinavia, Central and Eastern Europe, as 'district heating'. In many cities steam from centralized coal-burning power plants is piped to nearby residential areas (mostly apartment blocks) for domestic heating purposes. Unfortunately, even though the pipes are insulated, there are significant losses along the way and it is difficult to regulate the temperature at the end of the pipe, resulting in further inefficiencies, especially in the older East Europe applications. Also, the diversion of steam at a temperature above 100 deg. C. also reduces the efficiency of the electric power generating unit by several percentage points. District heating has not been widely adopted in the West for these reasons.

The theoretical gains illustrated in the illustration are not quite as easily achieved in practice as one might hope. There are multiple reasons, but the basic one is that the electric utility industry in most countries is a regulated 'natural' monopoly created to sell electricity, and not heat, under the (false) assumption that centralized power generation is more efficient than decentralized power generation. This was clearly true early in the twentieth century, but is no longer necessarily true. Relatively small gas turbines and Diesel engines are nearly as efficient as large steam generating systems, especially when transmission and distribution losses are taken into account. The next generation of high temperature fuel cells may be even more efficient. I comment further on these points below.

As regards the second strategy, it starts from the fact that many industrial processes produce under-utilized by-product energy streams. These include (1) hot exhaust gases, (2) combustible flare gases and (3) high pressure gases. Hot exhaust gases are produced by coke ovens, pelletizing ovens, glass furnaces, petroleum refineries, ammonia plants or hot rolled steel ovens. Flare gases are mainly produced by blast furnaces or petroleum refineries. High pressure gases are mainly from steam or natural gas pipelines, which must be reduced to ambient or near ambient pressure at the point of use. All of these can be used to generate electricity using commercially available equipment. Nevertheless, virtually all industrial facilities also utilize electric power, entirely purchased from the grid. The problem is to utilize the in-house waste energy streams to save on purchased electricity. Unfortunately, the electric utilities set discouragingly high prices on grid inter-connections and they pay low prices for purchased surplus power, mainly to discourage such competition.

Four examples follow:

Example #1. So-called ‘blast furnace gas’ at the US Steel works in Gary Indiana, consisting mostly of carbon monoxide and nitrogen, with some hydrogen and some carbon dioxide is a by-product of the iron smelting process. The monoxide and hydrogen make the gas flammable (and toxic), so it would have to be flared unless a beneficial use could be found. However at the US Steel works the gas has been captured to produce steam to power a steam turbine generator within the plant boundaries, with average electricity production of nearly 100 megawatts (MWe). The generating plant also extracts low pressure steam for process use throughout the mill and displaces boiler fuel. The mill saves nearly $20 million per year, after full capital recovery, and simultaneously avoids the use of 1.5 million barrels of oil equivalent per year, together with the carbon dioxide (and other pollutants) that would otherwise have been emitted..

Example #2. Exhaust gas from 268 coke ovens at Cokenergy in Northern Indiana has been directed to 16 heat recovery steam generators to produce 90 MWe of power and 1.3 million pounds of steam for the adjacent Inland-Ispat steel complex. This energy recycling process saves $58 million per year, after full capital recovery, and avoids 4.3 million barrels of oil equivalent as well as the associated pollution.

Example #3. Kodak’s main complex in Rochester New York stretches 5 miles end to end. It is now served by a multi-pressure steam system for the chemical processes on site. A steam extraction system has been built that recycles over 3 million pounds of steam per hour and generates roughly 150 MWe also used within the plant. The system saves nearly $80 million per year after full capital recovery and avoids 3.6 million barrels of oil equivalent per year.

Example #4. An Equistar plant in Illinois produces alcohol from natural gas feedstock with steam from a coal fired boiler. A back pressure steam turbine now recycles the high grade energy in the steam pressure to produce 16 MWe, saving $3.5 million per year after full capital recovery and avoiding roughly 100,000 barrels of oil equivalent per year.

These four examples illustrate the magnitude of possible reductions in the cost of energy possible from recycling the heat energy that is wasted unnecessarily by the arbitrary separation of electricity generation and process heat. In every case, these direct savings to the firm that invests in co-generation are only part of the story. Equally important are capital savings from avoided T&D investment, avoided transmission losses due to the lightened remaining load on local and regional wires, increased reliability of the grid (due to greater diversity of generators) and avoided emissions from boilers no longer needed to provide industrial steam or domestic/commercial space heating or hot water.

Official reports of the Energy Information Agency (EIA) show that only 9% of the total electric power generated in the US in 2000 was produced by facilities that recycled waste heat, even though many of them may have operated at a sub-optimal level in terms of the power-to-heat ratio. As of 2002 the Energy Information Agency (EIA) reported 806 combined heat and power plants in the US with 78 gigawatts (GWe) of "nameplate capacity" This was 7.13% of total installed capacity in the US.[ix] However, the potential is much greater. A recent study has identified 44 gigawatts (GWe) of additional capacity that could be powered with waste heat from just three source categories: flare gas from petrochemical processes, exhaust heat from the gas turbines that drive transcontinental gas pipeline compressors, and the utilization of steam pressure drop in industrial steam systems, as in the Kodak example (Casten and Collins 2002, 2003). That study omitted other industrial energy streams. Another recent study done for EPA has estimated that 95.7 gigawatts (GWe) of electric power could be provided in the US by recycled industrial waste heat in 19 industries. This would amount to 11.5% of current generating capacity in the US.

Yet, according to the 2003 Energy Information Agency (EIA) data, only 2.5 GWe of co-generation capacity was actually installed. Exploiting the full existing potential would save the US economy $4 to $10 billion per year *after full capital cost recovery* and avoid 200 to 500 million barrels of oil equivalent per year, not to mention the sulfur oxides, nitrogen oxides and carbon dioxide associated with the combustion of those fossil fuels. Even greater opportunities will arise in the coming years. The electrical supply industry has forecast that the US will need 137 GW of new capacity by 2010, costing $84 billion, plus $220 billion for additional transmission and distribution (T&D). Casten estimates that meeting this demand with decentralized CHP would cost only $168 billion, with no additional needs for transmission and distribution (*Table IV*). This translates into a saving of $.03/kWh.

There is a great disparity between states with power produced by CHP, ranging from 0% in three states to 22% in California and 25% in Hawaii. Of course the discrepancies are partly attributable to the mix of power production facilities, since hydroelectric plants are incompatible with CHP, and nuclear plants – as in France – are usually sited too far from cities to be able to provide district heating economically. International data show that combined heat and power (CHP) facilities generate roughly 7.2 % of the world's electric power, similar to the US percentage. But, according to national statistics, CHP accounts for over 50% of the electric power generated in Denmark, 39% in the Netherlands, 37% in Finland and 31% in Russia; Germany gets 19% and Poland, Japan, and China are at 18%. (Admittedly the high cogeneration (CHP) percentages in Russia, Poland, former E. Germany and China reflect long-standing policies of encouraging district heating combined with coal-burning central power plants.) These data indicate that CHP can be installed, provided the policies are friendly, that the plants are significant in size and burn all fuels, and that it is possible to recycle heat energy from a majority of electric generation facilities.

Misinformed opinion

A fundamental problem blocking reform is that policy-makers, regulators and the public assume that central generation is optimal. This was true early in the 20th century but is true no longer. Several unquestioned but incorrect assumptions underlie this fallacy. They include the following:

False assumption: Economies of scale guarantee that central power generation is more cost effective. **Correction.** It is still true that a new large plant can be built for fewer dollars per kilowatt of generating capacity ($500 to $1500) than a smaller plant using the same fuels and technology. However, this statement applies only to capital cost for the plant itself, not the fuel and not transmission and distribution (T&D), hence not the cost of power delivered to the user. There are several reasons. First, existing transmission system capacity in the US (and almost everywhere else) is overloaded . Adding a new central plant is not sufficient: transmission and distribution (T&D) capacity must also be increased to accommodate it. But, according to an Arthur D. Little study in 1999 each new kilowatt of central capacity requires an average of $1380 for new T&D wires. This increases the investment to $1880-$2880 per kW.

Moreover, average line losses from central power are 9% in the US. But the losses *under conditions of peak demand* are closer to 25%. This means that to supply a kilowatt of new peak load from a central plant to distant consumers, at times of peak load, one must construct 1.33 kilowatts of new generation and transmission capacity. This drives the investment up to between $2500 and $3840 per kW. In addition, central generation requires at least 15% reserve margin on top of expected peak loads. The cost of this reserve capacity ranges from $360 to $525. It follows that to add 1 kW of new capacity at a central plant one must actually build 1.56 kW of new central capacity and T&D at a total cost between $2875 and $4375, before paying for any fuel. In short, the real capital investment of new central capacity will be over 5.5 times the supposed minimum of $500/kW, and nearly 3 times the supposed maximum of $1500/kW.

Now consider a decentralized plant across the street from a customer. There is no need to add T&D capacity and there are virtually no line losses, because power is consumed either by, or virtually next door to, the producer. The new decentralized plant will replace the last leg of the distribution system, so it may require the addition of $100 to $200 per kW for wires, far less than the capital needed for adding the same capacity to a central system. These savings are additional to the fuel saving that arises from the fact that the decentralized plant saves boiler fuel that would otherwise be needed to provide heat to the customer. The World Alliance for Decentralized Energy (WADE) has built a model to take account of all of these factors to determine the optimal way to provide for expected electric load growth. The results from a number of model runs indicate that meeting all anticipated US load growth with decentralized generation would save $350 billion over the next two decades. This represents a reduction of 40% from the likely cost of meeting the demand from central generation alone.

The bar charts that follow (*Figure 2*) show recent estimates of energy savings, emissions reductions, capital savings and retail price savings for various assumptions about the use of decentralized CHP.

False argument: modern large combined cycle centralized plants (utilizing gas turbines and steam turbines in combination) can achieve up to 55% thermodynamic efficiency at significantly lower costs per kW, whereas smaller units in DCHP applications are significantly less efficient, and more polluting (Gulli). **Correction**. When the other advantages of CHP are considered, especially the additional T&D and reserve capacity requirements, the cost advantages of central plants are illusory. While it is true that most CHP applications require gaseous fuel, the same is true of the cited combined cycle plants, of which there are very few, whereas most electric power in the US is generated by aging coal-fired plants. Moreover, much of the domestic and commercial boiler fuel that would be replaced by DCHP is, in fact, natural gas. In other words, DCHP would help relieve the increasingly tight natural gas supply.

False argument: DCHP plants could fail at the same time the grid is experiencing peak loads, so the grid must enough additional redundant capacity to meet this demand. This is the argument regularly made by monopoly utilities to justify high standby rates. **Correction**. This argument applies only in the hypothetical case that there is one local generation plant on the entire utility grid, and that plant has only one generator. Since there are already 800 large distributed generation plants operating in the US, or an average of 40 per state, this hypothetical case is academic. Most DG plants have 2 to 8 generators that have random failure rates of between 2% and 4%. A grid with 100 DG plants connected thus has a probable failure rate of 2% to 4% of the DG capacity at any one time, including the system peak time. And, with a significant amount of DG capacity connected to a grid, system reliability can be achieved with less than the 15% to 20% redundancy needed by a grid served by only a few large central plants.

A recent study by the Carnegie Mellon Center for Electric Industry Analysis shows that a system based on many decentralized generation units located near users can achieve desired reliability with only 4% to 5% reserve margin, rather than the standard 15% reserve margin required by central plants (Zerriffi 2004). Putting it another way, depending on the percentage of power generated locally, the need for dedicated reserve capacity from the grid could range from 0% to 4%. The study cited above concluded *"Even without considering the benefits of robustness...a DG system offers substantial cost savings. Based on current IC engine cogeneration, and with utilization of only half of the cogeneration capabilities of IC engines, savings of up to 20% can be realized in the cost of electricity....These savings increase if more cogeneration is used (ibid. p.129)"*Other studies have led to similar conclusions (Lovins and Datta 2002; A. D. Little Inc. 2000).

The key to opening this reservoir of opportunities is deregulation of the electric power industry, especially by eliminating as many as possible of the barriers to competition listed in the text (Morgan and Zerriffi 2002; King and Morgan 2003). It should be emphasized that *there is no need to eliminate conventional centralized capacity*. The DCHP suppliers will have plenty to do in just meeting the demand increases already forecast for the next 20 years. Nor is there any reason to weep for the established utilities. Once the deregulation has occurred there is nothing to prevent them from getting into the DCHP business themselves. The end result will be a sharp increase in the overall efficiency of the US power system, and that of many other countries, with lower costs to consumers and less pollution of the environment.

Conclusions

Double dividends can and do exist in the modern world. The assumption that the economic system is always in equilibrium and that all technical subsystems are optimal is not only wrong but extremely dangerous, because it interferes with rational policy-making. The truth is that opportunities for savings can be found in many places. One major obstacle to finding them is inertia, or the assumption that there is nothing to find. Another obstacle is obsolete regulation from an earlier era.

On a more specific level, a very significant increase in the efficiency of fossil fuel use, with consequent reductions in GHG emissions and increases in system reliability, as well as reductions in consumer costs, can be had by the simple device of deregulating the US electric power distribution system. This would encourage many small producers to produce electric power and heat for local use while simultaneously remaining attached to the grid and providing reserve capacity for the grid.

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Endnotes

i. The existence of a static general equilibrium in such a system was finally proved in the 1930's by Abraham Wald for some special cases. More general proofs were given in 1954 by Kenneth Arrow and Gerard Debreu and by McKenzie (Arrow and Debreu 1954; McKenzie 1954) This achievement has steered a generation of economists into the analysis of highly abstract mathematical models. Actually, the rather tight restrictions of the original Walras model have been significantly loosened. The general equilibrium has even been extended to the dynamic case, with exhaustible resources (e.g. (Solow 1974), subject as before to the assumption of perfect futures markets for resources. A great deal of theoretical superstructure has been added on to this basic model in recent years, e.g. (Dasgupta and Heal 1979).

ii. Game theory, along with the modern form of utility theory, were introduced to economics by John von Neumann and Oskar Morgenstern (von Neumann and Morgenstern 1944).

iii. Actually it is not clear that savings and investment should be equated. Savings are not always invested productively. Egyptian pharaohs built pyramids. Medieval towns built cathedrals. Keynes told the story of the poet Alexander Pope's father, who retired from business to a Twickenham villa with a "chest full of guineas" from which he met household expenses thereafter (Keynes 1936) p. 221. French peasants are notorious for keeping their savings as gold coins, hidden under the mattress, while Indian women traditionally keep their dowries in the form of gold bracelets and other jewelry. Many modern millionaires collect old masters, large yachts and other symbols of wealth. Modern nations build strategic nuclear forces. None of these activities can be regarded as productive investment in any meaningful sense, however much pyramids, cathedrals and old masters created hundreds of years ago may have inadvertently added to the quality of life for people alive today. Surely investment in productive enterprise, or in R&D, must be explained otherwise — presumably in terms of expectations of future’supernormal’ profits.

iv. However, it has been shown that the condition of perfect competition can be relaxed without losing the possibility of competitive equilibrium; e.g. (Dixit and Stiglitz 1977; Ethier 1982; Grossman and Helpman 1989; Judd 1985). One cause of imperfect competition is, incidentally, increasing returns to scale of production (at the firm level). So, the co-existence of imperfect competition and increasing returns to scale do not *ipso facto* guarantee that the economy is not in equilibrium.

v. The technology life cycle is an important feature of the landscape. It is widely accepted as a useful metaphor of the pattern of technological change. The basic idea of an aging process goes back to "Wolff’s Law" of increasing marginal cost of improvement and Kuznets’ work on industrial succession and the business cycle (Kuznets 1930). It has been rediscovered and reformulated many times, especially by (Nelson 1962; Vernon 1966; Abernathy and Utterback 1975). Also see (Ayres 1988, 1994), Chapter 6.

vi. The economic literature is comprehensively reviewed in (Argote and Epple 1990). For a more technological approach, see (Ayres and Martinás 1992).

vii. The theory of `lock in’ (also known as `path dependence’) has been developed mainly by Brian Arthur (Arthur 1983, 1988).

viii. I can testify to this on the basis of personal conversations with senior Dow officials. I also wrote a letter to the CEO of Dow asking why Nelson had been treated so shabbily. I got a brush-off from a flunky.

ix. These CHP plants averaged 84 megawatts each. (The data do not include plants with less than 1 megawatt of capacity, so many micro-turbines and small diesel plants are not included.) By contrast, in the U.S. there were 3855 utility-owned or municipal electricity-only power plants with nameplate capacity of 863 gigawatts, averaging 224 megawatts per plant.