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9 Whither Flat Panel Displays?

Kala Krishna and Marie Thursby

In April 1994, the Clinton administration announced a $597 million policy initiative to encourage U.S. companies to invest in the research and development (R&D) as well as the large-scale production of flat panel displays (FPDs). Semiconductors have become a standard part of many manufactured products, and flat panel displays are seen as having a similar potential. In the near future, however, computers are likely to account for more than half of FPD demand. Recommended support for the National Flat Panel Display Initiative included $318 million for core research and development, $50 million for a manufacturing test bed, $199 million for R&D linked to volume production, and $20 million for procurement incentives. Among the initiative's goals is the creation of a U.S.-based industry capable of achieving a 15 percent share of the world FPD market by the year 2000 (Flamm 1994).

The initiative has been highly controversial (see Barfield 1994, 1995; Flamm 1994, 1995; Miller 1995; and Mowery 1995). While the Department of Defense (DOD) claims that domestic production of FPDs is critical for national security, critics label the initiative as misguided industrial policy. Citing surveillance experiences from Desert Storm and the growing importance of digital technologies, DOD officials argue that effective use of advanced information technologies will determine the winners of future military conflicts. Visual dis-

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plays are seen as a critical factor in this regard. Moreover, relative to cathode ray tube displays, FPDs are reliable, lightweight, and energy efficient. Thus, the DOD justifies the need for policy by citing limited U.S. capacity to produce FPDs and the apparent refusal of Japanese companies to tailor FPDs to DOD specifications (U.S. Department of Defense 1994).

Critics of the initiative argue that U.S. military demand for FPDs could be met easily by several small to medium-size plants, an increase in capacity much less than that required to capture 15 percent of the world market (Barfield 1994, 1995; Mentley 1994). DOD estimates of future military demand for FPDs are fifteen thousand annually from 1995 to 1999 and twenty-five thousand annually from 2000 to 2009 (U.S. Department of Defense 1994, III-14). Thus, even DOD estimates place defense needs for FPDs far below the initiative's goal of 15 percent of the world market. It is not surprising, then, that the initiative is considered by some to be thinly disguised industrial policy. In addition, it is also argued that the size of the initiative is too small for it to make much of a difference.

Viewed as such, a question of interest becomes whether the initiative will lead to an increase in output and whether these firms will earn economic rents.[1] Although this question has not been directly addressed, Mentley's market projections suggest that the initiative's output effects per se will be small relative to its goal. He claims that a 15 percent market share for U.S. companies would require an investment of $3 billion rather than the planned $600 million. Mentley's projected rates of return for active matrix liquid crystal displays also suggest relatively low profit margins beginning in 1995 (Mentley 1995).[2]

Another point of controversy is whether the initiative is consistent with post–Uruguay Round subsidy codes. Since R&D support under the initiative is limited to 50 percent of project cost, DOD officials argue that it is well within the 75 percent cap for subsidies for specific industrial research. Critics, such as Barfield, argue that the incentives for volume production are beyond precompetitive support and that the procurement incentives directly violate the new GATT codes. There are, however, exceptions to these rules for defense.

In this paper, we consider a related set of issues, namely, the effect of subsidies for core R&D and of subsidies targeted to high-volume production. We do this in the context of a model that we feel captures the importance of investment in capacity, as well as yield-improving R&D, in the flat panel industry. In this model, firms with higher yields, ceteris paribus, invest in more capacity than those with lower yields. This leads to higher capacity and output for high-yield firms. The model has the property that all firms that remain in the industry ultimately have the same yield, that is, in the steady state. Thus, firms with an initial advantage in terms of yields tend to remain ahead for a while, after

1. Of course, an important issue here is whether profit increases and/or spillover effects are sufficient to increase national welfare.

2. Lower profit margins are a result, in part, of increased world capacity with the recent entry by Korean firms (Pollack 1995).

which laggards catch up. However, note that this gives firms with higher initial yields a stream of quasi rents, which the laggards do not enjoy. Such characteristics are thought to apply to industries such as FPDs and semiconductors.

Relevant industry characteristics are discussed in section 9.1, and a simple, stylized model is presented in section 9.2. In section 9.3, we examine the fit between the cost structure postulated in the model and data on manufacturing costs for color thin-film transistor liquid crystal displays (TFTLCDs). Policy simulations are presented in section 9.4. We first look at a *permanent* 25 percent subsidy on capacity acquisition versus at 25 percent subsidy on yield-improving R&D. Our results suggest that capacity subsidies have the unfortunate effect of decreasing incentives for R&D.[3] This, in turn, leads the targeted firm to have lower steady-state yields with capacity subsidies than with either R&D subsidies or in the absence of policy.

We then compare the effects of a *one-shot* fixed expenditure by the government on capacity and R&D subsidies. This gives us an idea of the difference in leverage provided by the two instruments since the subsidies are specified as a *given dollar amount.* We find that this type of subsidy has a positive impact effect on the net R&D and capacity expenditure by firms when the subsidy is for R&D but not when it is a capacity subsidy! In our model, R&D subsidies tend to provide more leverage than capacity subsidies. Directions for future work are discussed in section 9.5.

9.1 The Industry

The flat panel industry provides an interesting case study, quite apart from the DOD initiative. It is a highly concentrated industry, in which survival depends on continual investment in both product and process R&D. Much like other high-technology electronics products, in the flat panel industry there are a variety of rival technologies undergoing development. Successful development of one technology does not guarantee profits for long because new technologies and new generations of old technologies are constantly being developed.

There are a multitude of interesting characteristics of the industry, and it is impossible to develop one model that captures all of them. Our model captures the idea that continual innovation is needed to reap profits. If a firm does not improve its yield, it falls behind. As the yields of its competitors rise, market price declines, eventually wiping out the lagging firm's profits, at which point

3. Care should be taken in relating the complex and difficult-to-implement DOD proposals to the simpler policies discussed here. According to U.S. Department of Defense (1994, I-9), "Selected companies committed to new investments in volume production facilities for current generation products would be eligible to receive R&D support for next generation products and manufacturing processes, commensurate with the level of commitment demonstrated to volume production." This makes the subsidy conditional on capacity acquisition, with the result that it can be interpreted as, in part, a capacity subsidy.

it exits. In focusing on the role of yield-improving innovation, we take several shortcuts. We assume that firms are concerned only with the current cycle of production, capacity acquisition, and R&D. They do not look forward to anticipate the effect of their behavior today on future cycles. We choose to do this because uncertainty about the future is high in this industry, making standard dynamic approaches ill suited for modeling it. In the interest of simplicity, we also neglect other features such as adjustment costs even though they are important in the industry. Capacity costs are likely to have a high sunk component leading to irreversibilities and adjustment costs. Adjustment costs of this kind create "hysteresis," and therefore history matters. This creates situations where a temporary policy or shock can have permanent effects by causing what looks like a regime change (see, e.g., Baldwin and Krugman 1989).

We abstract from several other factors, which, while important in the industry, have been studied elsewhere. Thus, including these factors would add little that is not already well understood. For example, some of the yield improvement observed in the industry is likely to result from learning by doing. Models of learning by doing are well studied in the literature. In a trade context, Baldwin and Krugman (1988) model the semiconductor industry in this manner. One result from such models is that firms produce more than they would if they equated marginal revenue and cost since they take into account the reduction in future costs implied by an additional unit of current output. In such contexts, capacity subsidies are in effect also R&D subsidies, making these models ill suited for answering the kind of questions we ask. That is, in learning-by-doing models, stark differences between R&D and capacity subsidies cannot be detected. We also assume that there are no spillovers in R&D. Such spillovers occur when a yield improvement by one firm accrues, at least partially, to other firms. Again, it is well understood[4] that spillovers of this kind reduce the ability to internalize the effects of R&D and hence tend to reduce the incentive to do R&D.

9.1.1 FPD Technologies

As shown in table 9.1, liquid crystal displays (LCDs) are the major type of display in today's market, constituting 87 percent of the commercial market. In these displays, light is emitted when voltage is applied to liquid crystals enclosed between the two sheets of glass (substrates) that make up the display.[5] Active matrix LCDs (AMLCDs), which control the polarization of these crystals by use of silicon transistors, are considered the dominant technology for high-information displays. The primary use of AMLCDs is as color screens for laptop computers. Passive matrix LCDs (PMLCDs) control light emission by use of metal horizontal and vertical electrodes on the two sheets of glass. PMLCDs are more commonly used than AMLCDs, but they have slower re-

4. For an analysis of R&D spillovers in an international trade context, see Jensen and Thursby (1987).

5. For a detailed description of each of the FPD technologies, see U.S. Department of Defense (1994, chap. 2).

Table 9.1 **Commercial FPD Sales**

	1993	2000[a]		1993	2000[a]
Total value (in $ billions)	6.5	20			
By technology (%):			By application (%):		
Nonemissive (LCD):	87	89	Computer	61	67
AMLCD	29	55	Consumer	12	14
Other	58	34	Business	9	5
Emissive:			Industrial	12	8
Plasma	4	4	Transportation	6	6
Electroluminescent	1	2			
Other	8	5			

Sources: U.S. Department of Defense (1994, figs. 2-1, 2-7, 3-1, 3-2); Stanford Resources (1994).
[a]Projections.

sponse times and tend to be less bright (U.S. Department of Defense 1994). Hence, as noted in the table, the DOD predicts an increase in the importance of AMLCDs relative to PMLCDs.

One problem with LCDs is that, even with redundant transistors at each pixel, some pixels fail to operate, with resulting quality problems in the display. LCDs are produced under the same clean-room conditions as semiconductors, and displays that contain defective pixels risk being discarded. This means that quality-control problems increase dramatically as the screen size increases, and therefore the potential of LCDs for large-screen applications is limited. Moreover, LCD producers engage in R&D to develop new generations of equipment that are capable of producing higher yields, that is, portion of production that is acceptable in terms of defective pixels.

Three alternatives to LCDs are plasma displays (PDPs), electroluminescent displays (ELDs), and field emission displays (FEDs). These displays differ from LCDs in that they produce their own light. PDPs generate light by applying voltage to an inert gas enclosed between the two sheets of glass, while ELDs and FEDs stimulate phosphors to emit light. Notice that these displays constituted only 5 percent of the market in 1993, and U.S. Department of Defense (1994) predicted that emissive displays will remain a small part of the commercial market in 2000. However, in August 1995, a number of companies announced progress toward development and production of PDPs and FEDs (Edmondson and Gross 1995; Patton and Rawsthorn 1995). Fujitsu, Matsushita, Sony, and NEC unveiled working prototypes of large-screen PDPs (up to forty-two inches), and Fujitsu announced plans to produce ten thousand units a month by October 1996. PDPs are considered to have the greatest potential for low-cost, large television screens.[6]

6. Notice in table 9.1 that the primary application of FPDs has been computers, with the consumer market representing only 12 percent of demand. While the DOD predicts a small consumer market in 2000, the evolution of cheaper large-scale FPDs is likely to increase the consumer market dramatically.

9.1.2 Market Shares in FPDs

As with VCRs, the technologies leading to FPDs were developed in the labs of U.S. electronics companies, but the industry is now dominated by Japanese companies.[7] For example, early technologies for FPDs were developed in research labs at RCA, Westinghouse, and IBM in the 1960s and 1970s. Engineers in RCA's Sarnoff Lab developed LCD technology with the goal of developing a television screen "flat enough to hang on a wall" (U.S. Department of Defense 1994, chap. 6). Peter Brody, of Westinghouse, developed the cadmium selenide AMLCD technology underlying the majority of today's AMLCDs. Although these technologies were at the prototype stage, neither RCA nor Westinghouse pursued commercial development of FPDs. RCA switched from LCD to cathode ray research in the 1970s, while Westinghouse dropped its project in 1979. In the 1970s, IBM pursued plasma technologies for computers and business applications, but, in 1984, it switched R&D efforts to LCD technologies. In the late 1980s, IBM and Toshiba formed Display Technologies, Inc. (DTI), a joint venture for the development and high-volume production of LCDs in Japan. None of these companies invested in manufacturing capacity in the United States.[8]

In contrast, companies such as Sharp and NEC actively pursued development and production of FPDs. Both companies stood to benefit from their experience with the types of clean-room conditions and continual process improvements important in semiconductors. Sharp successfully applied FPD technology to handheld calculators in the 1970s, and in the 1980s it became a leader in color TFTLCDs. In 1993, Sharp was the world's largest producer of FPDs, with its sales constituting 44 percent of the world market. NEC and DTI were the next largest producers, with sales constituting 35 percent of the market (U.S. Department of Defense 1994, chap. 4).

In total, approximately fifty companies manufacture FPDs. As noted in table 9.2, Japanese companies accounted for over 90 percent of the LCD market in 1993. Seven Japanese companies accounted for 98 percent of the AMLCD market. In 1993, the only volume producer of AMLCDs in the United States was Optical Imaging Systems, which primarily sold displays for avionics applications. If one views IBM's joint venture, DTI, as a Japanese company, the only markets in which U.S. companies are large players are the PDP and ELD

7. The patent underlying virtually all VCR technologies was obtained by Ampex Corp., a U.S. company, in the late 1950s. Although Ampex successfully commercialized a videotape recorder for broadcast use, the first companies to commercialize a consumer product were Sony, JVC, and Matsushita. This occurred despite early efforts by RCA to develop a consumer video recorder and a joint venture by Ampex and Toshiba for the same purpose. For an analysis that focuses on the role of government policy in VCR development, see Tyson (1992). In contrast, Rosenbloom and Cusumano (1987) take the view that the evolution of the industry is due primarily to different management styles of the companies involved.

8. For an account of other efforts by U.S., European, and Japanese companies, see U.S. Department of Defense (1994, chap. 6).

Table 9.2 **1993 Market Shares by Country (%)**

	LCD	AMLCD	Plasma	Electroluminescent
Japan	92	98	68	47
United States	1	1	19	50
Other	7	1	13	3

Sources: U.S. Department of Defense (1994, figs. 4-1, 4-2, and table 4-1); Stanford Resources (1994).

markets. The fact that these markets constitute only 5 percent of the total value of LCDs (table 9.1 above) is one aspect of the DOD's justification for the flat panel policy initiative.

Several U.S. companies are conducting R&D on FPDs, in part as a response to the DOD initiative. Optical Imaging Systems was awarded an Advanced Research Projects Agency (ARPA) contract to construct a new AMLCD plant, and it is involved in a joint venture with Apple to develop displays for computer applications. Additionally, a consortium formed by AT&T, Standish Industries, and Xerox received a DOD award to develop a manufacturing test bed. Various other R&D projects are ongoing at Motorola, Raytheon, Sarnoff Labs, and Texas Instruments.

9.2 A Simple Model

In this section, we develop a simple model that we feel captures several important features of the flat panel display industry. First, we feel that the timing structure needs to recognize that output is easier to change than capacity, which in turn is easier to change than yield. We therefore assume that, in what we call the short run, both capacity and yield are fixed. In what we call the medium run, capacity is variable, and, in the long run, yield can be chosen. Of course, in the steady state of such a model, long-run and short-run yields must be equal.

Second, we feel that, in the short run, with capacity and yield as given, firms behave competitively and take price as given. Thus, their only decision is whether to produce to capacity.[9] If profits are nonnegative, firms produce; and, if profits are negative, firms do not produce. However, in the medium run, they choose capacity. In making this decision, they take into account the fact that capacity affects output and hence profit. This results in a capacity choice equilibrium resembling a Cournot-Nash equilibrium. In the long run, firms choose R&D expenditure, which affects their yields, and hence their capacity

9. The clever reader will immediately think of a counterexample where the last firm's capacity, if used entirely, results in negative profits but, if not used at all, results in a price higher than short-run marginal cost. It is argued below that this case will never arise. The argument consists of showing that capacity choices of this kind are never made.

choice, as well as output. Notice that we abstract from R&D to develop new types of FPDs, with the result that the only R&D is for process improvement.

Third, firms with a high yield find it easier to attain a given yield higher than their existing one than do firms with lower yields. However, any improvement in yields is costly. It is also assumed that there are positive costs of any improvement in yields, no matter how infinitesimal. The latter assumption permits convergence of the yields to a finite level in some steady states.

We wish to use the model to answer questions about the evolution of industry capacity. If, for example, a given number of firms start off with different yields, what should we expect for their capacity and yield paths over time? Do firms that have better yields invest more or less in R&D? Do firms with better yields stay ahead in terms of yields? If there is entry into the industry, will profits be eroded to zero? Does the final profile of an industry depend on the initial profile? How?

By examining these questions, we hope to shed light on the effect of policies designed to encourage investment in R&D and in production facilities. We find that firms with higher yields, ceteris paribus, invest in more capacity than those with lower yields. Since firms produce up to capacity, this implies more output by these firms. Higher outputs, in turn, increase the benefits from investments in R&D to raise yields. As our simulation results show, this conflagration of forces plays a role in the effects of capacity and R&D subsidies. While capacity subsidies initially lead to increased capacity and hence investment in yields, at the margin they reduce the benefit from yield-increasing R&D. As shown in section 9.3, this can lead to steady-state yields that are lower than what would occur without the capacity subsidies. In contrast, subsidies to R&D promote higher steady-state yields.

9.2.1 The Short Run

Assume that there are N firms in the industry. Each firm i has a capacity of S^i and a yield of y^i. The production process can be thought of as being composed of two steps. In order to have one viable unit of production at the end of the first stage, $1/y^i$ units need to be started at a cost of c_1 per unit started. This corresponds to the idea that only y^i percent of the FPDs are usable since panels have to be discarded if any pixels are defective. Following this, further stages of production must be performed on the viable unit at a cost of c_2 per unit. Thus, the total cost of q^i units of produced output in the short run for a firm with yield y^i and capacity S^i is

$$(1)\qquad \mathrm{TC}^i_{sr}(q^i, y^i, S^i) = \left(\frac{c_1}{y^i} + c_2\right)q^i \text{ for } q^i \leq S^i$$
$$= \infty \text{ for } q^i > S^i.$$

Such firms have a short-run marginal cost of $\mathrm{MC}^i_{sr} = c_1/y^i + c_2$. Profits are thus

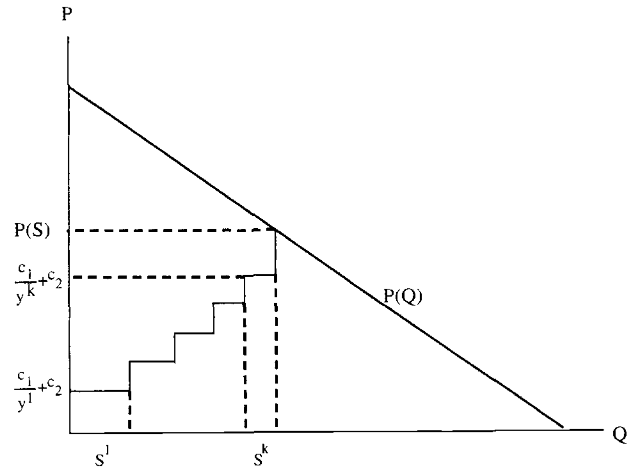

Fig. 9.1 Short-run equilibrium

$$(2) \qquad \Pi^i_{sr}(q^i, y^i, S^i) = P\left(\sum_{j=1}^{k} q^j\right)q^i - \left(\frac{c_1}{y^i} + c_2\right)q^i \text{ for } q^i \le S^i$$
$$= -\infty \text{ for } q^i > S^i.$$

The supply curve for the industry is as depicted in figure 9.1. As firms behave competitively, each firm supplies its entire capacity if price exceeds its marginal cost. This permits us to replace q^i with S^i whenever a firm makes positive profits. It also results in the step-function form of supply depicted. Firms take the intersection of demand and supply as the given price, and they maximize their profits accordingly in the short run. As drawn, firms with lower indices have higher yields and correspondingly lower marginal costs. Only firms with indices less than $k + 1$ supply as drawn in figure 9.1.

9.2.2 The Medium Run

In the short run, firms take their capacities as given as well as their yields. In the medium run, they take only their yields as given, and they choose capacities. The cost of an additional unit of capacity is F^i, but a firm that has a yield of y^i will incur a cost of $(F^i/y^i)q^i$ to get an output of q^i. Of course, firms realize that their choice of capacity affects the price in the market and incorporate such considerations in their decision making. Each firm, therefore, chooses its capacity, S^i, to maximize its medium-run profits, which along with its first-order condition are given below:

$$(3) \qquad \Pi^i_{mr}(y^i, S^i, S^{-i}) = P\left(\sum_{j=1}^{k} S^j\right)S^i - \left(\frac{c_1}{y^i} + c_2\right)S^i - \frac{F^i}{y^i}S^i,$$

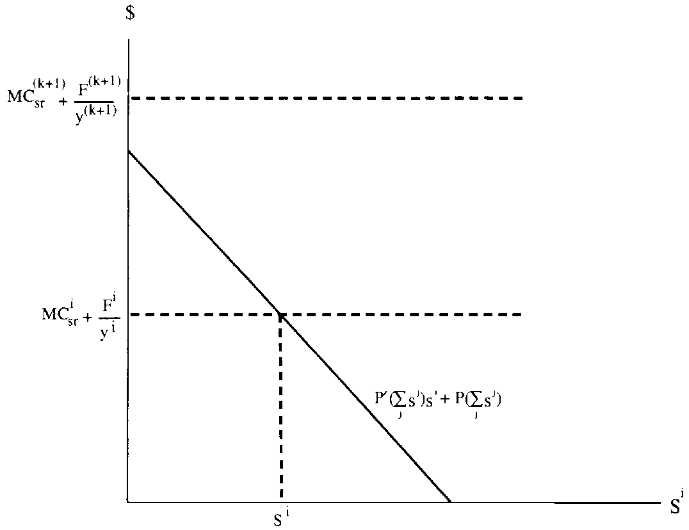

Fig. 9.2 Medium-run equilibrium

$$\text{(4)} \qquad \frac{\partial \Pi^i_{mr}(y^i, S^i, S^{-i})}{\partial S^i} = P'\left(\sum_{j=1}^{k} S^j\right)S^i + P\left(\sum_{j=1}^{k} S^j\right) - \left(\frac{c_1}{y^i} + c_2\right) - \frac{F^i}{y^i} = 0.$$

Figure 9.2 depicts the capacity choice that solves (4). Note that, if a firm chooses to invest in capacity, its profits in the short run must be *strictly positive.*[10] Hence, firms will choose to produce all their capacity in the short run.

As all firms choose their capacities in this manner, the solution to this system looks like a Cournot-Nash equilibrium. The equilibrium levels of S^i are denoted by $S^i(y^1, y^2, \ldots, y^N)$ for $i = 1, \ldots, N$. Notice that firms with higher yields will choose higher capacity levels, as one would expect.

9.2.3 The Long Run

In the long run, firms choose their yield levels realizing how this affects the outcome in the short and medium runs. The cost to a firm with yield y^i_0 of raising its yield to level y^i is denoted by $R^i(y^i_0, y^i)$. We will assume that this takes a particular functional form given by

$$\text{(5)} \qquad R^i(y^i_0, y^i) = z(y^i - y^i_0) + \theta(y^i - y^i_0)^2.$$

10. If $P(\sum_{j=1}^{k} S^j) - c_1/y^i - c_2 = 0$, then the lowest-yield firm may produce less than its full capacity. It is easily shown that the medium-run equilibrium rules out capacity choices that will not be used in the short run.

Note that this functional form has the property that even small improvements in yield are costly and that larger improvements become progressively more costly.

Thus, in the long run, firm i wishes to maximize its long-run profits given by

$$(6)\quad \Pi^i_{lr}[y^i, S^i(\cdot), S^{-i}(\cdot)] = P\left[\sum_{j=1}^{k} S^j(\cdot)\right]S^i(\cdot) - \left(\frac{c_1}{y^i} + c_2\right)S^i(\cdot) - \frac{F}{y^i}S^i(\cdot) - z(y^i - y^i_0) - \theta(y^i - y^i_0)^2.$$

The first-order condition, after using the envelope theorem, gives

$$(7)\quad \frac{c_1}{(y^i)^2}S^i(\cdot) + \frac{F}{(y^i)^2}S^i(\cdot) - R'(\cdot) + P'(\cdot)S^i(\cdot)\sum_{j\neq i}\frac{dS^j(y^1, \ldots, y^n)}{dy^i} = 0.$$

In addition to the long-run first-order condition given above, we need a steady-state condition for each firm. In the steady state, the yield chosen by each firm must equal its initial yield. The steady-state condition for each firm, therefore, consists of equation (7), where $R'(\cdot)$ is evaluated at $y^i = y^i_0$.

9.3 Costs and Yields

In this section, we examine data for costs of production at various yields to get an idea of the importance of yield differences in the industry. Cost data are from Stanford Resources (Mentley and Castellano 1994; Stanford Resources 1994). They refer to a portion of the AMLCD market, namely, color TFTLCDs produced in 1994.

In the short run, recall that each firm produces up to capacity, as long as its short-run costs fall short of price, with costs given by $(c_1/y^i + c_2)S^i$ if their yield is y^i. Mentley and Castellano report unit costs for final output levels (q^i) between 60,000 and 960,000 panels per year and yields between .1 and .9. These unit-cost data include variable costs such as materials, supplies, and equipment as well as direct and indirect labor employed in producing color TFTLCDs. They also include capital investment cost in the form of depreciation.[11] For our analysis of short-run cost, we compute the unit cost net of depreciation. On the basis of these data (net of depreciation), the following regression was estimated to give us estimates of c_1 and c_2:

$$(8)\quad TC^i = \tilde{c}_1\frac{q^i}{y^i} + \tilde{c}_2 q^i + \varepsilon$$

11. Mentley and Castellano report high- and low-cost figures for unit costs and depreciation. The regressions reported here are based on their high-cost figures. Regression results using low costs are similar to those reported here and are available from the authors. For procedures used to compute the unit-cost data, see Mentley and Castellano (1994). Their depreciation figures are based on straight-line depreciation over five years.

Table 9.3 **Cost Regressions**

	Dependent	
Independent	Total Variable Cost	Total Fixed Cost
q/y	47.12	51.82
	(7.03)	(.21)
q	554.13	
	(29.09)	
R^2	.93	.99
No. of observations	45	45

Source: Mentley and Castellano (1994).
Note: Standard errors are given in parentheses.

Coefficient estimates and standard errors are reported in table 9.3. The form seems to fit the data well, with an R^2 of .93.

Note that a two-stage cost structure is embodied in this cost function. A fraction y of the starts are nondefective at the end of the first stage. The cost of the first-stage application is c_1. Thus, to get one unit past the first stage, $1/y$ units are needed as starts with a cost of c_1/y per nondefective unit at the end of the first stage. At the second stage, the cost is c_2 per unit that goes in. Our estimates suggest that variable cost levels rise sharply with reductions in yield, especially at low-yield levels.

Our specification of medium-run costs also depends on yields. That is, $TC^i_{mr} = (c_1/y^i + c_2)S^i - (F^i/y^i)S^i$, where the last term reflects capacity acquisition cost. As noted above, Stanford Resources also reports data for capacity cost in the form of depreciation. Since these data are reported for final output levels between 60,000 and 960,000 panels per year and yields between .1 and .9, we can examine the importance of yields in medium-run cost. We estimate a regression of the form

$$\text{TFC}^i = \tilde{F}\frac{S^i}{y^i} + \varepsilon \tag{9}$$

As noted in table 9.3, our estimate of $\tilde{F}$ is 51.82, and the R^2 is .99.[12] Thus depreciation on flow capacity costs and hence also plant costs depend on yield.

Taking both estimates into account, it appears that plants with yields of 30 percent or more are viable at 1994 prices. That is, with a yield of 30 percent, variable costs are about $710 per unit, and capacity costs are approximately $170, while the December 1994 price was around $1,000. With a 20 percent yield, variable costs are about $790 per unit, and capacity costs are about $260 per unit. In our model, a firm with this yield would show negative medium-run profits at the 1994 price.

12. Such a high R^2 makes us suspect that the capacity cost data, in particular, come from accounting procedures that replicate our model.

9.4 Simulation Results

In this section, we focus on policy experiments in a simple two-firm version of our model. We do this for several reasons. First, while the cost equations in our model show a good fit with the data, other data and/or elasticity estimates needed to calibrate the model are not publicly available. Second, the model's equilibrium conditions, especially those for long-run equilibrium given by (6) and (7), are highly nonlinear. This makes it difficult to solve the system analytically with many asymmetric firms. We therefore simulate a simple two-firm system to obtain some insights into policy issues.

We focus on two policy experiments. In the first, we look at the effects of a *25 percent permanent subsidy* to R&D or to capacity acquisition. In the second, we look at the effects of a given *one-time subsidy* on either R&D or capacity. In both experiments, we show how the results depend on the degree of asymmetry between the firms.

The model is the same as in the previous sections. For simplicity, we assume a linear form for the market demand curve, which is parameterized as

$$P\left(\sum_{j=1}^{2} S^{j}\right) = a - b\left(\sum_{j=1}^{2} S^{j}\right). \tag{10}$$

Short-run profits are given by (2), medium-run profits by (3), and long-run profits by (6). In each of the simulations, we look at the evolution toward the steady state of key endogenous variables, including yields, capacity, price, and profits. Our purpose in carrying out these simulations is to help understand the possible consequences of proposed subsidies to R&D and to volume production in the flat panel industry. Will subsidies to capacity acquisition help or hinder the long-run competitiveness of the targeted firm? Are such subsidies likely to raise or reduce welfare?

9.4.1 A 25 Percent Subsidy

We first consider the case of two identical firms. We trace the behavior of the simulated market over time under three scenarios. The first is that of no policy. The second is that of a 25 percent subsidy on capacity for one firm, call it firm A, so that F is reduced by 25 percent for firm A alone. The third is that of a 25 percent subsidy on R&D expenditure, which corresponds to a 25 percent reduction in z and θ for firm A. We then repeat the above three simulations for the asymmetric case where firm A has a lower yield than firm B. This allows us to examine the effects of an initial disadvantage on the results of the policy experiments.

In each case, the parameters we use are as follows. The slope of the inverse demand curve, b, and its intercept, a, are set at $b = 1$ and $a = 37$. The marginal costs in the short run are given by $(c_1/y^i + c_2)$ for firm $i = $ A, B. We set $c_1 = c_2 = 1$. In the symmetric case, both firms have the same yield of .5, and therefore $y^A = y^B = .5$. In the asymmetric case, $y^A = .4$, and $y^B = .5$. The cost of obtaining a unit of capacity is F and is common to both firms. We set $F = 2$ throughout. The cost parameters in yield-increasing R&D are z and θ, and these are common to both firms and set at $z = 120$ and $\theta = 1{,}000$.

The Symmetric Case

In the symmetric case, given yields of .5 each, both firms choose a capacity of 10. The market price to start with is 17, short-run marginal cost of each firm is 3, and short-run profits are 140 each. Capacity costs are 40 per unit, and medium-run profits are 100. We run the system through thirty iterations. At each iteration, yields rise, capacity rises, profits rise, and price falls. Yields rise to .583, which is close to the steady-state level of .586. Capacity rises to 10.28, while price falls to 16.43. On the other hand, expenditure on yield-improving R&D falls dramatically to .06 from a starting value of 2.12.

When we reduce the cost of capacity acquisition by 25 percent to firm A, the immediate response in the first iteration is an increase in the chosen capacity to 10.67. In response to this, B's capacity choice is to keep capacity slightly below 10. In addition, A invests less in yield-improving R&D than before and has a lower yield as a consequence! While B invests more than A, its investment in R&D also falls from that with no policy in response to A's reduction in R&D. Initially, A invests 1.12, and B invests 1.85. Both these numbers are below those that would occur in the absence of policy.

The impact effect of the subsidy is to raise A's gross profits and lower B's. Over time, A's profits rise but then begin to fall, while B's rise throughout. The reason for this is that a capacity subsidy (which reduces F) encourages capacity investment, as is evident from (4). However, incentives to do R&D are also *diminished* by the subsidy on capacity costs. The reason is apparent from the first-order condition given in (7). This equation can be thought of as choosing y_i on the part of firm i to equate the marginal benefit of yield-improving R&D,

$$\left[\frac{c_1}{(y^i)^2} S^i(\cdot) + \frac{F^i}{(y^i)^2} S^i(\cdot) + P'(\cdot) S^i(\cdot) \sum_{j \neq i} \frac{dS^j(y^1, \ldots, y^n)}{dy^i}\right],$$

with its marginal cost, $R'(\cdot)$. If the problem is well behaved, we can think of the marginal benefit as decreasing in y^i. The marginal cost is increasing in y^i for our specification, starting from any given initial yield. Recall that a capacity subsidy reduces F by 25 percent. This shifts the marginal benefit curve of doing yield-reducing R&D inward, reducing the chosen yield.

In contrast, a subsidy to R&D reduces $R'(\cdot)$ by 25 percent in (7). This shifts the marginal cost of yield-reducing R&D down and out, raising the chosen level of y^i. This in turn *reduces* the marginal cost of a unit of capacity as seen in (4), and this raises capacity acquisition in the medium run.

At the end of thirty iterations, A has a yield of .544, while B has a yield of .579, both of which are *less* than that without policy! A's capacity exceeds that of B (10.68 vs. 10.08), and price falls to 16.25. R&D expenditure falls to .002

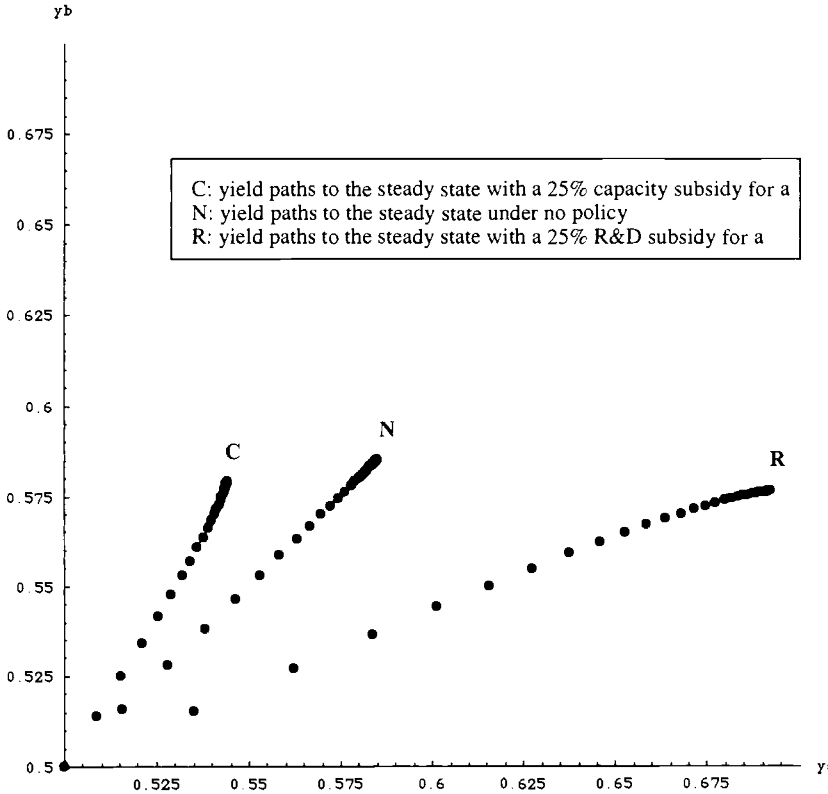

Fig. 9.3 Yield paths to the steady state in the symmetric case with y_0^A = .5 and y_0^B = .5

for A and .013 for B, both of which are lower than they would be without the policy. Profits in the short run initially go to 142.6 for firm A and 133.8 for firm B as a direct consequence of the higher capacity induced by the subsidy. After thirty iterations, short-run profits go to 143.2 and 136.2, respectively.

In contrast, an R&D subsidy of 25 percent results in an impact effect that almost doubles A's R&D expenditure, which goes to 4.07, while B's goes to 2.06. Both firms' R&D expenditures fall steadily over time to .03 and .005, respectively, after thirty iterations. Firm A's capacity rises steadily over time to 10.8, while B's stays at about 10. Yields also rise steadily to .692 and .576 for A and B, respectively. A's short-run profits rise throughout, while B's fall throughout, ending up at 148.7 and 134.2, respectively, after thirty iterations. Price falls to 16.15 at the end of thirty iterations.

It is perhaps easiest to compare the effects of the three policies on yields by looking at figure 9.3. Each point is an iterative value of yields for A and B. Yields are always increasing. In the first iterations, there are large changes in

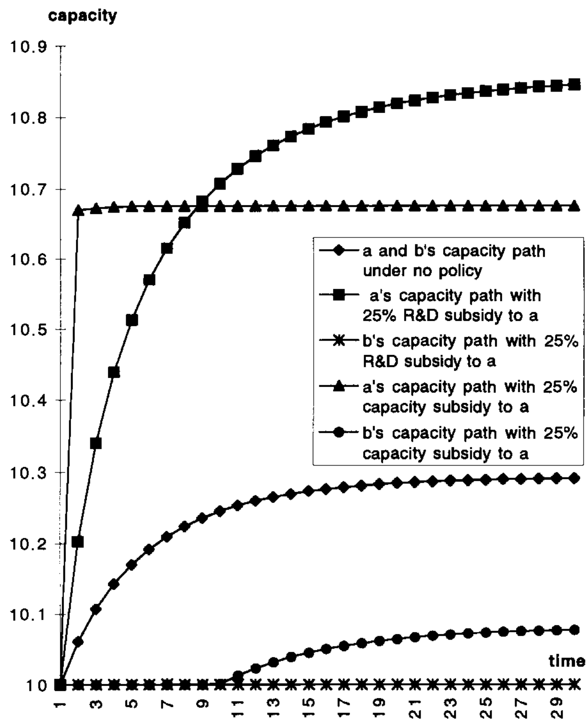

Fig. 9.4 Capacity paths to the steady state in the symmetric case with $y_0^A = .5$ and $y_0^B = .5$

yields, but these get smaller over time, as depicted by the dots moving closer together as yields rise. The *R* curve, which gives the yields with the R&D subsidy, always lies to the right of the *N* curve, which depicts the yields with no policy. The *C* curve always lies to the left of the *N* curve. Thus, while B reaches roughly the same yield across the three scenarios, A's yields vary considerably, being lowest in the capacity subsidy case and highest in the R&D subsidy case. Figures 9.4 and 9.5 depict the capacity and short-run profit paths as a function of time for the two firms across the three scenarios.

The Asymmetric Case

While the simulations above provide useful insights, it is important to ask about the extent to which they are modified by firm A being at an initial disadvantage. To cast some light on this, we repeated our simulations for starting values of yields of .4 for A and .5 for B. Without any policy, A's initial disadvantage is slowly overcome. A invests significantly more in R&D than B, and the two firms arrive at the symmetric steady state as before. When a capacity subsidy of 25 percent is given, the same kinds of effects are obtained as in the symmetric case. While A's investment in R&D remains above B's, it falls be-

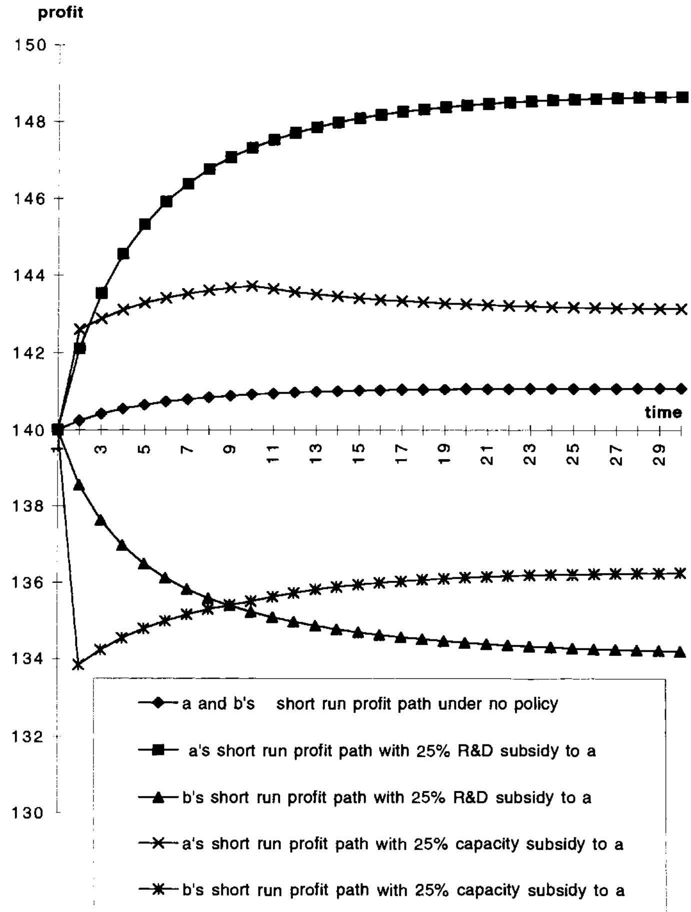

Fig. 9.5 Short-run profit paths to the steady state in the symmetric case with $y_0^A = .5$ and $y_0^B = .5$

cause of the subsidy. However, even after thirty iterations, the yield of firm A remains below that of firm B, .543 versus .579! In contrast, with an R&D subsidy, A's yields surpass those of B after only seven iterations. By the end of thirty iterations, the yields are at .691 and .576, respectively.

Thus, asymmetries in the initial yields only seem to magnify the differences in the two policies. With initial asymmetries, firm A needs to invest heavily in R&D to catch up with firm B. A capacity subsidy reduces the incentive to do R&D, and, as a result, A's yield remains below B's. By contrast, an R&D subsidy enhances the incentives to do R&D, and A's yield, short-run profits, and capacity overtake B's in a small number of periods. The behavior of yields in the asymmetric case is depicted in figure 9.6. Again, each point is an iterative value of yields for A and B. Yields are always increasing, and, at first, there are

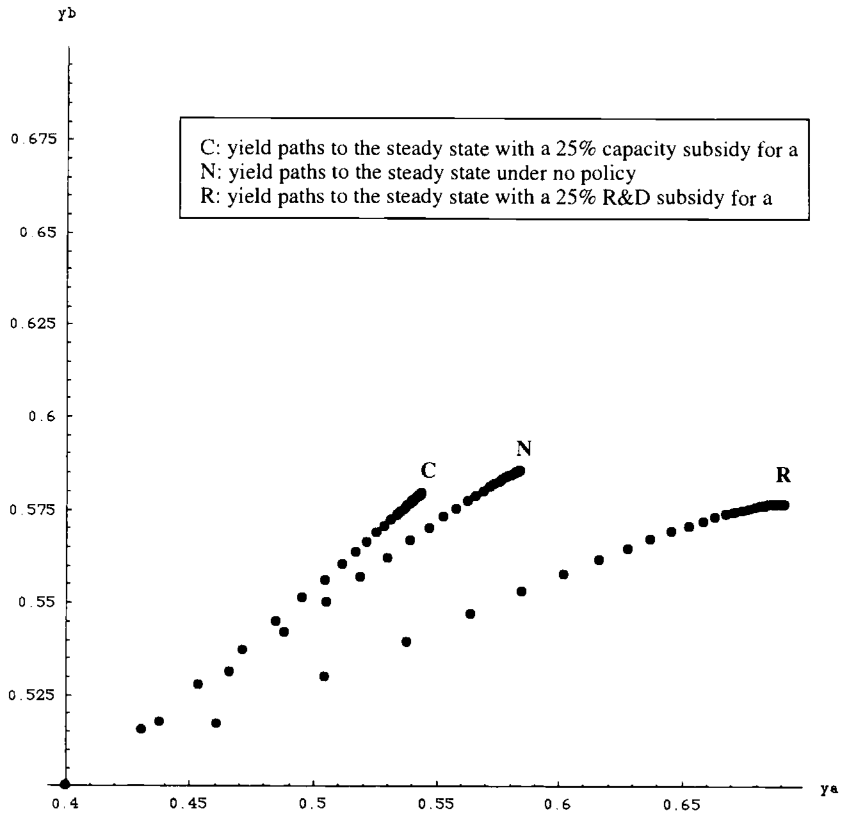

Fig. 9.6 Yield paths to the steady state in the asymmetric case with $y_0^A = .4$ and $y_0^B = .5$

large changes in yield, but these get smaller over time, as depicted by the dots moving closer together as yields rise. The *R* curve, which gives yields with the R&D subsidy, always lies to the right of the *N* curve, which depicts the yield with no policy. The *C* curve always lies to the left of the *N* curve. Again, while B reaches roughly the same yield across the three scenarios, A's yields vary considerably, being lowest in the capacity subsidy scenario and highest in the R&D subsidy scenario. Figures 9.7 and 9.8 depict the capacity and short-run profit paths as a function of time for the two firms across the three scenarios in the asymmetric case.

9.4.2 A Given Subsidy Expenditure

The results so far suggest that R&D subsidies seem to be more effective than capacity subsidies. The reason is that an R&D subsidy raises yields, which in turn effectively reduces the cost of a unit of capacity and encourages capac-

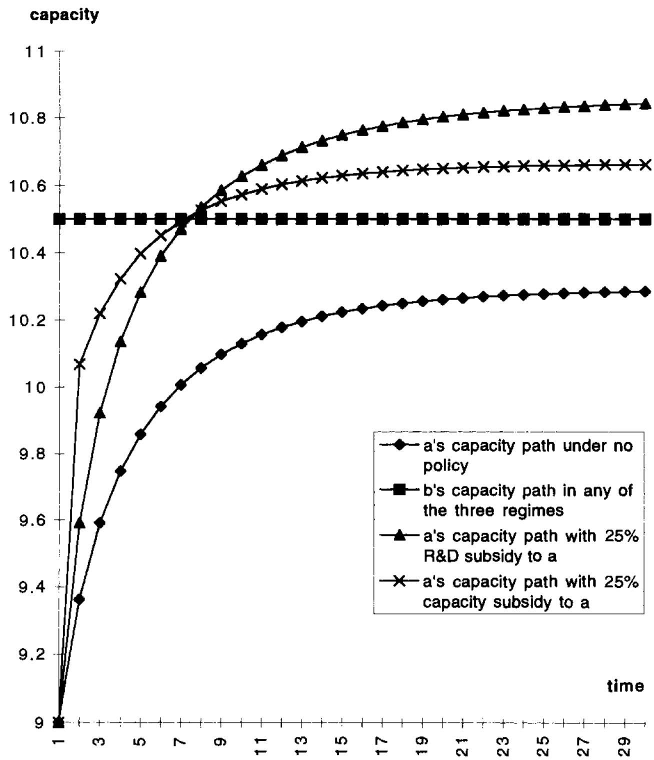

Fig. 9.7 Capacity paths to the steady state in the asymmetric case with $y_0^A = .4$ and $y_0^B = .5$

ity acquisition, while a subsidy on capacity raises the incentive to do capacity acquisition but reduces the incentive to do yield-improving R&D.

The simulations so far compare a given permanent (25 percent) subsidy on R&D with one on capacity. They do not compare the effects of a given, one-shot expenditure on the two kinds of subsidies, which is, of course, the relevant comparison for the allocation of given funds to alternative policies. Such a simulation would also address another criticism of the DOD initiative: namely, that it is *too small* to produce the desired effect. It is obvious that a dollar spent on R&D or capacity subsidies need not result in exactly a dollar increase in gross expenditure. It could result in more than a dollar increase in gross expenditure, in which case net expenditure (expenditure net of the subsidy) rises, or it could result in less than a dollar increase in gross expenditure, in which case net expenditure falls!

First, note that, in our earlier simulations, yields and capacity stabilize as the steady state is reached, with the result that R&D and capacity expenditures fall over time. If we simulate the effects of a one-time subsidy, the immediate

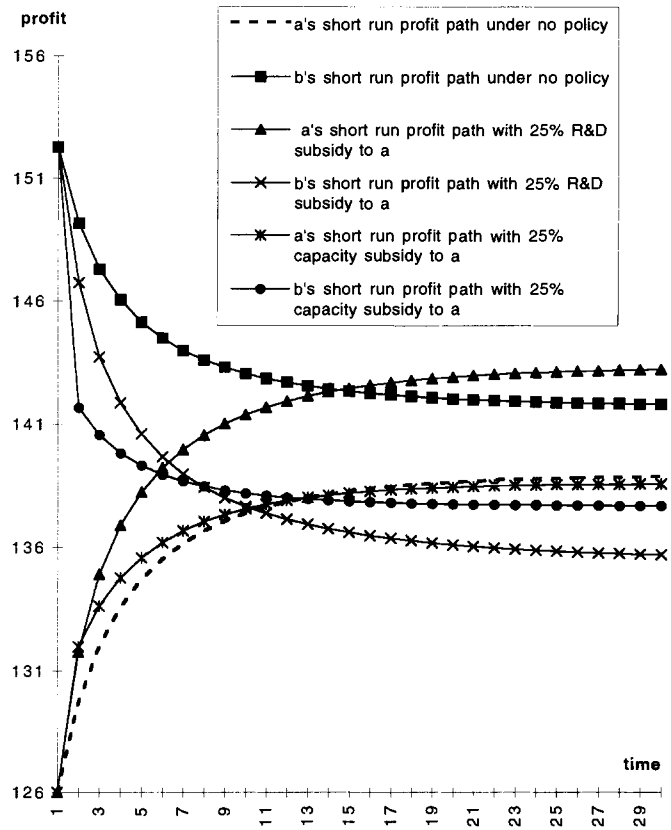

Fig. 9.8 Short-run profit paths to the steady state in the asymmetric case with $y_0^A = .4$ and $y_0^B = .5$

effect will be to raise the gross level of the targeted variable above its no-policy path, but, when the subsidy is removed in the next period, these higher levels cannot be sustained. In the model that we use, there is no effect of a one-shot policy on the steady state. However, this does not mean that these policies have no effect: the path to steady state is very different under the two policies.

Figure 9.9 plots the *net* effect of a $1.00 subsidy (applied as the equivalent ad valorem level) when applied to R&D and to capacity in the symmetric case. The dashed line in the figure plots the difference between the targeted firm's R&D expenditure (net of the government subsidy) when it receives a one-shot dollar subsidy for R&D and its R&D expenditure without policy. The cross-hatched line plots the difference in the firm's capacity expenditure (net of the subsidy) with and without this R&D subsidy. The solid and dotted lines have the same interpretations when the policy is a one-shot subsidy for capacity

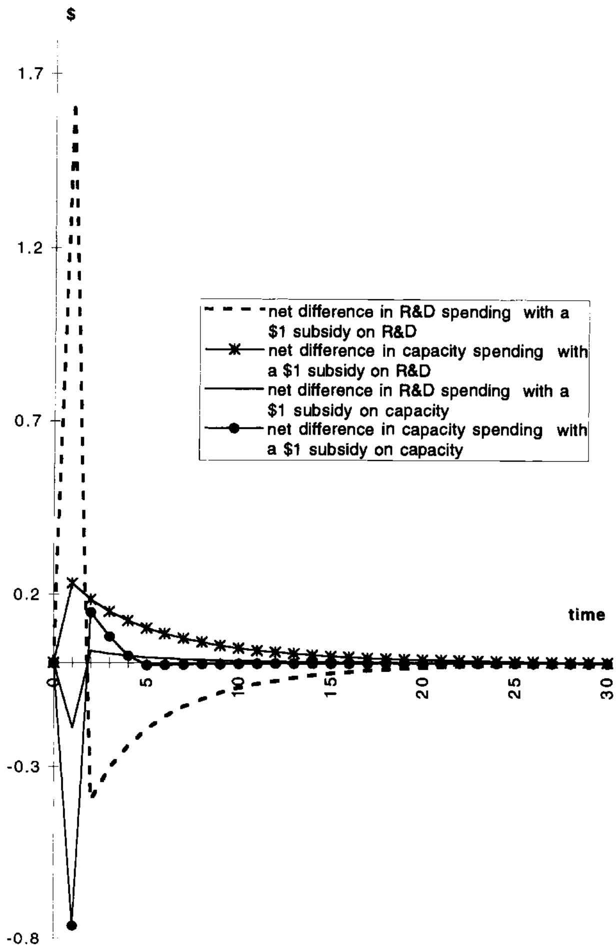

Fig. 9.9 Net effects of $1.00 subsidies for the symmetric case with $y_0^A = .5$ and $y_0^B = .5$

acquisition. We focus on these plots since the path of yields and capacity can be inferred from them.

A dollar spent on R&D results in an immediate increase in *gross* expenditure on R&D of about $2.62, and therefore net expenditure rises by about $1.62, as shown in figure 9.9. Of course, in the following period, expenditure on R&D falls below that with no policy. However, this reduction is only about .4, with the result that the impact effect dominates. This results in the path of yields lying above the no-policy path. Moreover, the impact effect of the R&D subsidy on capacity expenditure is to raise it above its no-policy path, as shown in figure 9.9. This is because, as discussed earlier, higher yields reduce the cost of investing in capacity and so result in a greater incentive to invest in capacity. Thus, capacity also lies above its no-policy path in this case.

In contrast, a dollar spent on a capacity subsidy results in an impact effect of a net reduction in expenditure on capacity acquisition of about −.76! In other words, gross expenditure rises by only .24 as there is crowding out of private expenditure by the government subsidy. In addition, expenditure on R&D falls as a capacity subsidy reduces the incentive to invest in R&D, as argued earlier. In subsequent periods, there is a small positive effect on R&D and capacity expenditures relative to the no-policy path, which fades out over time, with the capacity expenditure becoming negative in some later periods.

Figure 9.10 plots the *net* effect of a $1.00 subsidy (applied as the equivalent ad valorem level) when applied to R&D and to capacity in the asymmetric case with firm A's yield reduced from .5 to .3. The four curves have the same interpretation as in figure 9.9 above.[13] First, note that a dollar spent on R&D results in an immediate increase in *gross* expenditure on R&D of only $1.68, and therefore net expenditure rises by about $0.68, as shown by the dashed line in the figure. To understand this, recall that, with asymmetric firms, if the laggard (firm A) does not drop out, it spends more on R&D than the firm that is ahead in order to catch up. With a convex R&D cost function, the more R&D that is done, the more expensive is further R&D. This, plus the fact that steady states are independent of initial conditions as long as the firms remain in the market, makes a given dollar subsidy on R&D translate into a smaller equivalent percentage in the asymmetric case (as compared to the symmetric one). While both factors reduce the effectiveness of R&D subsidies in the asymmetric case, the qualitative conclusions drawn in the symmetric case remain. As before, capacity acquisition is encouraged by the R&D subsidy, and, in subsequent periods, R&D expenditure falls below that with no subsidy at all.

A capacity subsidy of a dollar initially reduces and then raises R&D expenditure. Net expenditure on capacity falls by about .61 as the gross expenditure rises by only .39. In contrast to the symmetric case, however, expenditure on capacity does not rise above the no-policy level in subsequent periods. These simulations thus suggest that R&D subsidies dominate capacity subsidies if the aim is to raise yields and capacity. They also suggest that R&D subsidies have greater leverage in the symmetric case as they have a larger net impact effect under these circumstances.

9.5 Concluding Remarks

The public debate on flat panels has focused largely on whether the Clinton administration initiative is clever promotion of dual use technology or straightforward industrial policy. In contrast, we examine whether subsidies to promote volume production ($199 million of the initiative) or R&D subsidies

13. The intermediate case where firm A's yield is .4 shows effects similar to these.

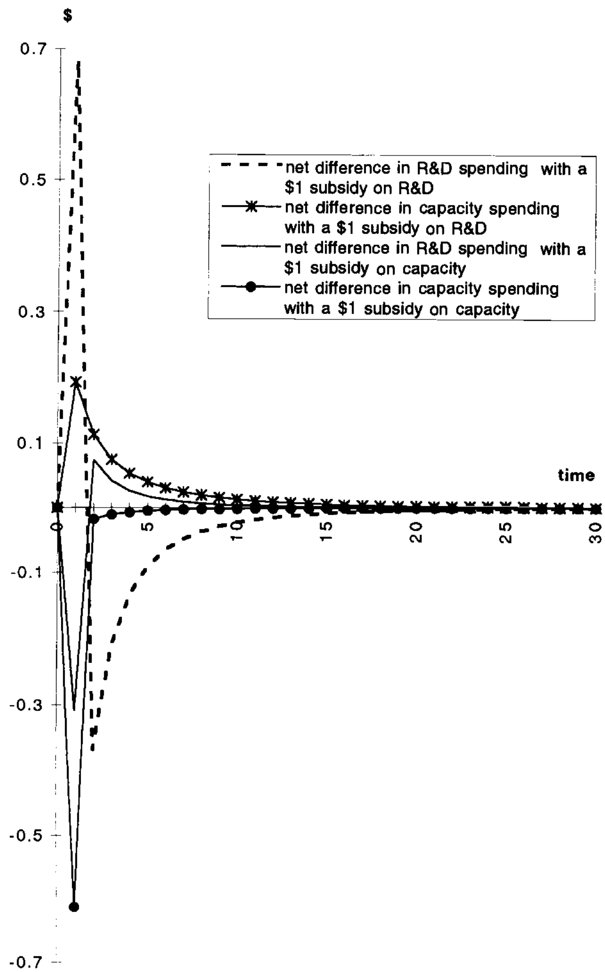

Fig. 9.10 Net effects of \$1.00 subsidies for the asymmetric case with y_0^A = .3 and y_0^B = .5

(\$318 million of the initiative) are more effective. Our results suggest that R&D subsidies provide the government more leverage in supporting an industry. In the context of our model, subsidies for capacity can, in fact, backfire because they reduce a firm's incentive to invest in yield-improving R&D. As always, these results should be interpreted in the context of the model and its exclusions. For example, the inclusion of learning by doing would make our distinction between R&D and capacity subsidies less clear. Perhaps the most interesting revision would be to see how the inclusion of forward-looking behavior by firms would affect our results with and without policy.

Our model can be used to examine other issues, such as the effects of entry. The effect of entry is important for the flat panel industry, not only with respect to entry of U.S. firms, but also with respect to recently announced capacity increases of Korean firms (Pollack 1995). It is entirely possible that profits are not eroded to zero by entry because entrants use technologies with lower yields than incumbent firms that have done the necessary R&D to maintain higher yields.[14]

An additional issue of interest is how the initial configuration of firms' capacities and yields determines final industry configuration. Indeed, we suspect that firms that enter early can remain and earn profits later on when new entry is not viable! These issues, as well the effect of R&D or capacity subsidies on the final configuration of firms and the minimum size of subsidies necessary to accomplish particular goals, are left for future work.

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14. Hence, new firms have disincentives for entry. Incumbent firms realize that raising capacity will reduce price, and this results in their voluntarily limiting their capacity. Thus, it is likely that, despite firms choosing output competitively, profits are nonzero owing to quasi rents that arise.

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