SANDIA REPORT SAND81-1618 • Unlimited Release • UC-62
Printed November 1981

A Game Theory Approach to Consumer Incentives for Solar Energy

John K. Sharp

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

When printing a copy of any digitized SAND Report, you are required to update the markings to current standards.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.
NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: $9.00
Microfiche copy: A01

SAND81-1618
Unlimited Release
Printed November 1981

Distribution
Category UC-60

A GAME THEORY APPROACH TO CONSUMER INCENTIVES FOR SOLAR ENERGY

John K. Sharp
Photovoltaic Systems Development Division 4723
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

Solar energy is currently not competitive with fossil fuels. Fossil fuel price increases may eventually allow solar to compete, but incentives can change the relative price between fossil fuel and solar energy, and make solar compete sooner. This paper develops examples of a new type of competitive game using solar energy incentives. Competitive games must have players with individual controls and conflicting objectives, but recent work also includes incentives offered by one of the players to the others. In the incentive game presented here, the Government acts as the leader and offers incentives to consumers, who act as followers. The Government incentives offered in this leader-follower (Stackelberg) game reduce the cost of solar energy to the consumer. Both the Government and consumers define their own objectives with the Government determining an incentive (either in the form of a subsidy or tax) that satisfies its objective. The two hypothetical examples developed show how the Government can achieve a stated solar utilization rate with the proper incentives. In the first example the consumer's utility function guarantees some purchases of solar energy. In the second example, the consumer's utility function allows for no solar purchases because utility is derived only from the amount of energy used and not from the source of the energy. The two examples discuss both subsidy and tax incentives, with the best control over solar use coming from fossil fuel taxes dependent upon the amount of solar energy used. Future work will expand this static analysis to develop time varying incentives along a time and quantity dependent learning curve for the solar industry.

This work was supported by the U. S. Department of Energy

A GAME THEORY APPROACH TO CONSUMER INCENTIVES FOR SOLAR ENERGY

Introduction

Solar energy incentives can improve the relative economics between solar and fossil fuel. Presently, solar energy is not economical when compared to fossil fuel, but with future fossil fuel price increases and solar energy price decreases, solar may become competitive in certain locations. Government incentives can help make solar energy competitive sooner by stimulating and developing the solar industry. The resulting solar production increases will lower system costs. Determining the proper incentive mix for the Government to offer is a major problem because consumers' and suppliers' reactions to the incentives must be considered. The economic problems associated with initial overstimulation and/or discontinuous stimulation can be avoided with the proper incentive program. The Government acting as a leader can offer incentives which encourage consumers to purchase more solar energy. By calling the Government a leader and the consumers followers, a generalized problem can be developed where the leader has his own objectives, and he is trying to influence purchases of the followers who have their own objectives. In the literature, this type of leader-follower game is called a Stackelberg game[1]. Solar incentives will now be analyzed using Stackelberg game theory.

Game theory[2] is the study of players who can act upon and change a system. Players attempt to make favorable changes in their individual cost or objective functions. Games are either cooperative or competitive with the players acting accordingly. Stackelberg games[3,4] are competitive and contain two types of players: a leader and followers. The leader in a Stackelberg game knows how the followers react to him, and he uses this information to choose his most desirable action. Game theory has recently been used to investigate incentives in public decisionmaking[5]; incentives have also been used with Stackelberg games to investigate duopolies.[6]

Solar Incentives Using Stackelberg Games

Incentive theory for solar energy can be developed using Stackelberg games. The ultimate goal of an incentive program is to make solar energy competitive with other energy forms. If this goal is not

achieved, then incentives must be continued after the solar industry has matured. This time varying problem can be treated as static if intermediate targets are set for the solar industry. The Government acting as a leader has a specific short-term target it hopes to achieve with incentives while consumers acting as followers have their own objectives. The Government's short-term objective could be a production target while the consumers' objectives are to maximize their well-being (commonly referred to as utility in economics) subject to the funds they have available with which to purchase energy. Using the single consumer case, these conditions can be expressed analytically as:

Leader (Government) Objective: achieve a stated goal J

$$J = f_{\ell}(q_1, q_2) \tag{1}$$

Follower (Consumer) Objective: maximize utility U

$$U = f_f(q_1, q_2) \tag{2}$$

Subject to:

$$I = p_1 q_1 + p_2 q_2 \tag{3}$$

where:

q_1 = units of fossil energy

q_2 = units of solar energy

p_1 = price per unit of fossil fuel

p_2 = price per unit of solar fuel

I = total consumer budget for energy products

The model described by (1) - (3) does not include Government incentives. In this model the consumer maximizes his utility subject to the budget constraint to determine his purchases q_1* and q_2* (with q* denoting the optimal purchases). These values determine the deviation from the Government's objective. The three types of Government incentives available to change the consumers' energy mix are:

1. Solar energy subsidy
2. Fossil energy tax
3. Rationing and/or regulating energy purchases

A solar energy subsidy allows the consumer to purchase more solar energy with the same amount of funds. Fossil fuel taxes decrease the amount of fossil fuel that can be purchased and encourage the use of

solar energy by reducing the relative price between solar and fossil energy. Rationing fossil energy forces consumers to switch to solar for additional energy, and regulating or requiring more solar usage increases the demand for solar. The budget constraint (3) modified to account for subsidy and tax incentives is:

$$I = p_1q_1 + p_2q_2 + tq_1 - sq_2 \tag{4}$$

where:

t = per unit fossil fuel tax

s = per unit solar

Rationing or regulating is where both s and t are zero, and the Government determines the value of q_1 or q_2.

The subsidy or tax must ensure that, when the consumer acts in his own best interest, the Government's objective is realized. The Government can achieve this by first characterizing the consumers' reaction to various taxes and/or subsidies. This information is then used as a constraint when the Government tries to achieve its objective. Two hypothetical examples are presented which show how the Government can determine the necessary incentives to achieve a targeted production level of solar energy.

Stackelberg Example 1

The two examples differ only in the utility derived by the consumer from energy. In both examples the Government's objective is to achieve a targeted solar production level. This production level is assumed to be a point along a learning curve for the solar industry. The first example assumes a standard consumer utility function which is the fossil fuel usage times the solar energy usage.

The competitive game occurs when the consumer tries to maximize his utility subject to his budget constraint while the Government tries to achieve the targeted level of solar energy usage. The objective functions and budget constraint for this example are:

Leader's (Government's) Goal: minimize the target solar production error

$$J = (q_2 - 0.4)^2 \tag{5}$$

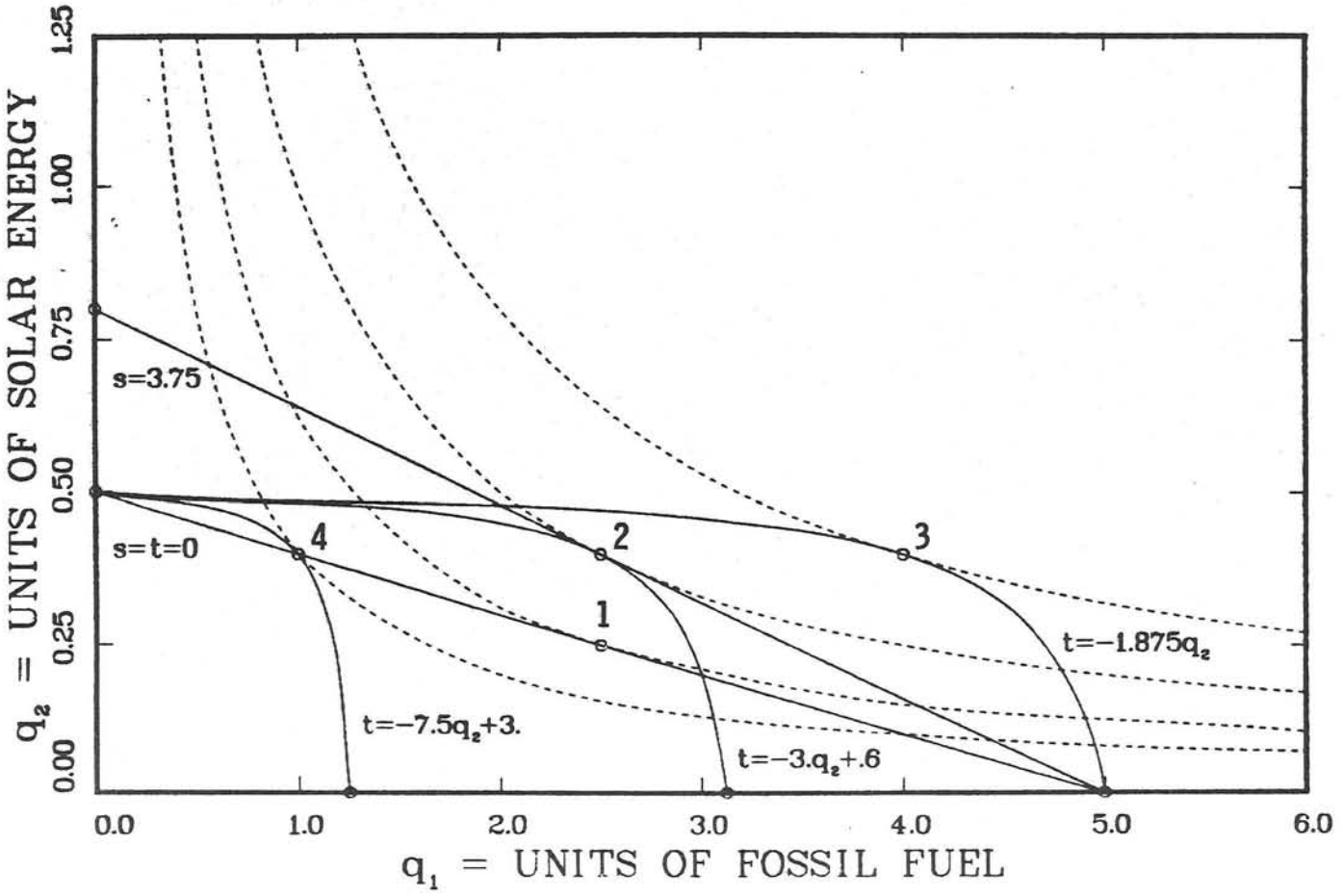

Figure 1. Impact of Incentives on The Consumer's Energy Use Assuming a Standard Utility Function

Followers' (Consumers') Goal: maximize utility

$$U = q_1 q_2 \tag{6}$$

Subject to the budget contraint:

$$5 = q_1 + 10q_2 + tq_1 - sq_2 \tag{7}$$

Solar and fossil energy have the same energy units with the Government's targeted level of solar energy usage being 0.4 unit. The consumers' total budget for energy products is 5 and the unit prices of fossil fuel and solar energy are 1 and 10, respectively. Thus, solar energy is assumed to cost ten times as much as fossil energy currently costs. Without incentives, the consumer can purchase up to 5 units of fossil energy or 0.5 unit of solar energy. This budget constraint is shown as a straight line between the (5, 0) and (0, 0.5) points in Figure 1. The consumer's desired place on the budget line is point 1 where his utility is maximized. Solar energy usage is only 0.25 unit which is less than the Government's targeted usage of 0.4 unit. Incentives are needed to encourage the consumer to use more solar energy.

At point 2 the Government's target solar level is achieved with either a subsidy or tax and fossil fuel use is not increased: either a subsidy of \$3.75 per unit of solar energy or a tax on fossil fuel of $-\$3.00\ q_2 + \$0.60$. The tax on fossil energy is a function of the amount of the consumers' solar energy usage. A straight tax on fossil energy similar to the solar subsidy decreases fossil energy usage, but it does not guarantee more solar usage. For the standard utility function, the share of income for purchasing solar or fossil energy remains the same; so, when the price of fossil fuel is raised through direct taxes, the amount of fossil energy consumed is reduced with no effect on solar energy consumption. This is why, at point 2, the solar subsidy increased the use of solar energy with no effect on the use of fossil energy; but if either a tax or subsidy is used to move the consumer to point 2, he is better off than he was at point 1. Thus, the individual would benefit from the incentive program because the Government must increase the consumers' energy budget to achieve the targeted solar energy level.

The targeted solar level is achieved at point 3, but the use of fossil fuel has increased. The necessary tax is $-\$1.875\ q_2$ per unit of fossil fuel. The budget line, including this incentive, has end points equal to the initial budget line. The consumer is better off at point

3 than at point 1 because he can now purchase more solar energy and more fossil fuel. With this subsidy the consumer is not only paid to increase his use of solar energy but also to increase his use of fossil energy.

Point 4 is located on the budget line, but since it has less utility than point 1, it was not initially chosen. This point would be chosen if the tax were $-\$7.50\ q_2 + \$3.00$. The net government cost at this point is zero (i.e., taxes equal subsidies) because the point is on the original budget curve. This point can also be attained by rationing fossil fuel to one unit or by regulating solar energy usage to 0.4 unit.

With the proper mix of subsidies and taxes, any point in the $q_1 - q_2$ plane can be made desirable to the consumer, providing that q_1 is less than I/p_1. A major problem with using the standard utility function for solar energy analysis is that both types of energy must be used or the utility is zero. In most processes where solar energy is a feasible substitute for fossil fuel, the total amount of energy is more important than having some of each type. This suggests that a plausible objective for the consumer may be obtaining the most energy possible within the budget constraint.

Stackelberg Example 2

The second example shows how a consumer reacts if he desires to maximize the amount of energy used. This is also equivalent to minimizing the per unit cost of energy. The Government's goal (Eq. (5)) and the consumer's budget constraint (Eq. (7)) are the same, but the consumer's utility is now:

$$U = q_1 + q_2 \tag{8}$$

The utility curves are straight lines denoting equal energy usage. The value of a unit of energy is the same to the consumer, no matter where it comes from. Subsidies and taxes are again investigated using this new utility function.

Point 1 on Figure 2 is the desired energy mix without subsidies or taxes. Since utility is defined as the total amount of energy, the optimal mix is to buy on the cheapest; and in this case, fossil fuel. Thus, solar is not initially being used, so subsidies and taxes must be offered before solar penetrates the market.

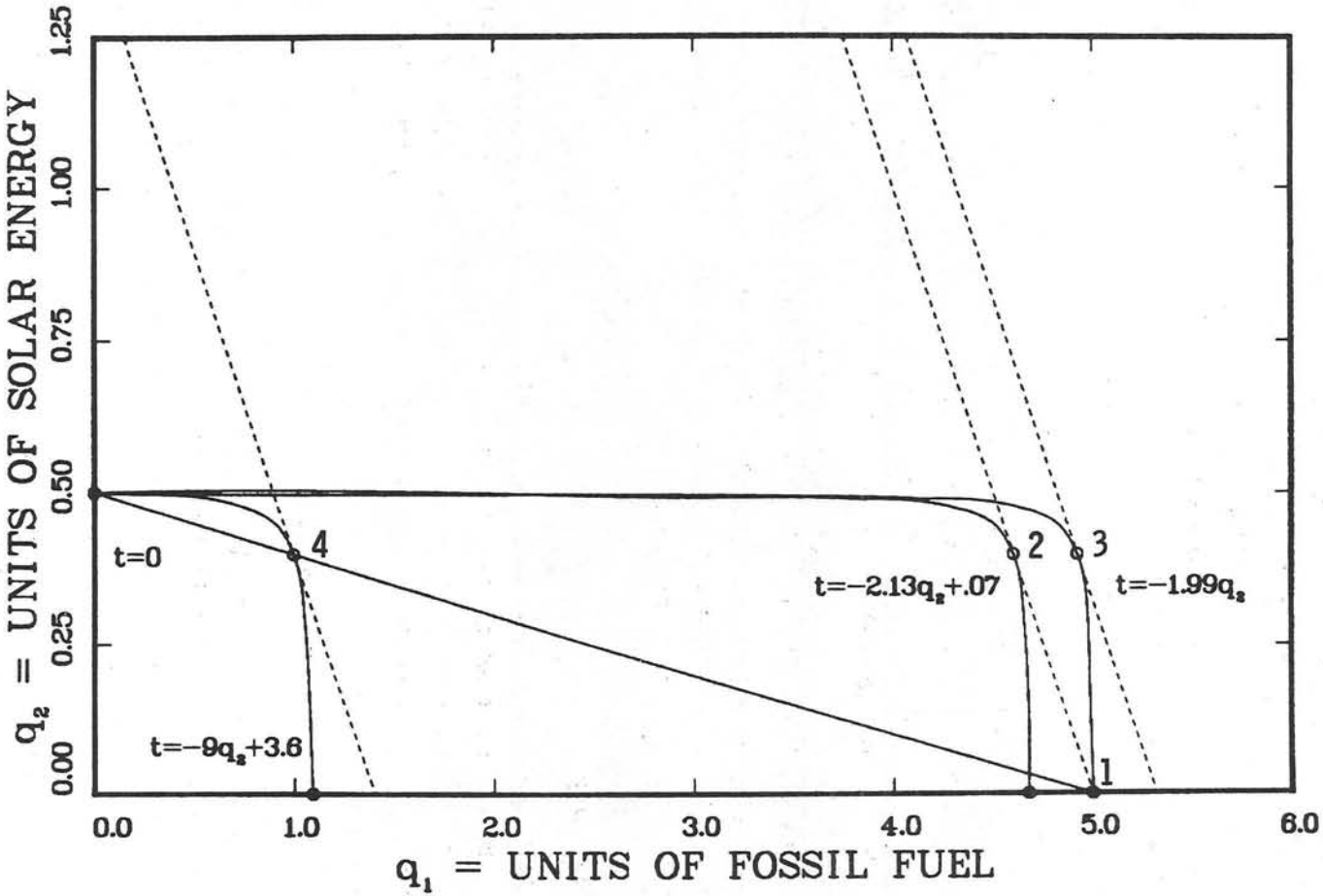

Figure 2. Impact of Incentives on the Consumer's Energy Use Assuming Total Energy as the Utility Function

The desired energy mix at point 2 requires a tax of $-\$2.13\ q_2 + \$0.07$. The total energy usage has not increased (i.e., point 1 and point 2 are on the same utility curve), but 0.4 unit of fossil fuel has been displaced with solar energy. Since the consumer utility has not been reduced, the Government must pay for 90 percent of the solar energy used.

At point 3, the higher utility means greater energy usage. The tax of $-\$1.99\ q_2$ is equivalent to a government payment of 98 percent of the solar energy costs. The boundary points on the budget line are the same as the no-tax case, so the fossil fuel user is not penalized if he decides against participation in the solar incentive program.

Point 4 is on the original budget line so the net cost to the Government is zero, but the utility (i.e., energy use) has been severely reduced. This point can also be achieved by regulating or rationing.

For a solar subsidy to impact the energy mix, it must be set to at least 90 percent of the solar costs because of the ten-to-one price ratio between solar and fossil energy. Unless the 90 percent subsidy is limited, large-demand impulses would destabilize the solar sector of our economy. The tax scheme outlined above stimulates interest in partial displacement of fossil energy with solar and provides better government control over solar energy demand.

Conclusion

The initial theoretical development of leader-follower games involving solar incentives has been presented. The game theory approach forces policymakers to evaluate potential incentives against defined objectives. From this theoretical work, Example 2 indicates that incentives in the form of a tax, rather than straight solar subsidies, may provide for more control of solar demand by the Government. The static results from this analysis can be expanded to develop proper incentives for various points on the solar industry learning curve. The evaluation of how incentives affect multiple consumers and/or producers is a straightforward extension of the present analysis.

REFERENCES

1. H. von Stackelberg, The Theory of the Market Economy, (1952), Oxford University Press, Oxford, England.

2. J. Case, "Toward a Theory of Many Player Differential Games," SIAM J. on Control, 7, (1969), pp 179-97.

3. M. Simaan and J. B. Cruz, Jr., "On the Stackelberg Strategy in Nonzero-Sum Games," JOTA, 11, (1973), pp 533-55.

4. M. Simaan and J. B. Cruz, Jr., "Additional Aspects of the Stackelberg Strategy in Nonzero-Sum Games," JOTA, 11(1973), pp 613-26.

5. J. Green and J. Laffont, Incentives in Public Decision Making, (1980), North-Holland Pub. Co., New York, NY.

6. M. A. Salmon and J. B. Cruz, "An Incentive Model of Duopoly with Government Coordination," Automatica, V. 17, Nov. 1981 (to appear).

Distribution:

Solar Information Center
1536 Cole Blvd.
Golden, CO 80401
Attn: R. Ortiz

Solar Energy Research Inst. (3)
1536 Cole Blvd.
Golden, CO 80401

Jet Propulsion Laboratory (3)
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: J. Becker
J. Lucas
K. Terasawa

Office of Technology Assessment
U. S. Congress
Washington, DC 20510
Attn: R. Rowberg

U. S. Dept. of Energy (3)
Albuquerque Operations Office
P. O. Box 5400
Albuquerque, NM 87185
Attn: G. N. Pappas
C. B. Quinn
J. Weisiger

U. S. Dept. of Energy (5)
Division of Energy Storage Systems
Washington, DC 20545
Attn: J. Gahimer

U. S. Dept. of Energy (8)
Division of Solar Thermal Energy Systems
Washington, DC 20585
Attn: W. W. Auer
G. W. Braun
J. E. Greyerbiehl
M. U. Gutstein
L. Melamed
J. E. Rannels
F. Wilkins
J. Dollard
J. Easterling

U. S. Dept. of Energy (2)
San Francisco Operations Office
1333 Broadway, Wells Fargo Bldg.
Oakland, CA 94612
Attn: R. W. Hughey

4000 A. Narath
4700 J. H. Scott
4710 G. E. Brandvold
4713 J. V. Otts
4714 R. P. Stromberg
4715 R. H. Braasch
4716 J. F. Banas
4717 J. A. Leonard
4720 D. G. Schueler
4721 W. P. Schimmel
4723 D. G. Schueler (Actg)
4724 E. C. Boes
4726 E. L. Burgess
4750 V. L. Dugan
5510 D. B. Hayes
5513 D. W. Larson
5520 T. B. Lane
5523 R. C. Reuter
8326 C. T. Yokomizo
8430 R. C. Wayne
8431 P. J. Eicker
3141 L. J. Erickson (5)
3154-3 C. Dalin (25) for DOE/TIC
3151 W. L. Garner (3) (Unlimited Release for DOE/TIC)
6011 Patents
4723 J. K. Sharp