# Evolutionary Game Analysis For Sustainable Environment Under Two Power Generation Systems

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# Evolutionary Game Analysis For Sustainable Environment Under Two Power Generation Systems

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**Abstract**: With the rapid prosperity of the global economy and industry, as the energy demand, many factors influence power-producing sectors, including government incentives, customer demand, production cost, eco-friendly, and investors investment. To analyze the cost-benefit-subsidy in power generator system under the evolutionary game setting, we considered two asymmetric game structures by coupling the photovoltaic (PV) power system and coal-fired (CF) power system. To model the asymmetric games for PV and CF, Game-1 considers respective cost and benefit, whereas, Game-2 deliberates cost, benefit, and government subsidy. We present both analytical and numerical approaches within this framework.

Keywords: Evolutionary game theory; power generator system; Government subsidy.

## 1. Introduction

The Photovoltaic (PV) power system, one of the essential energy systems, implies that this power system can mitigate the power demand. The PV system using the solar potential to power generation provides benefits such as low maintenance, minimum environmental effect, and moderate power generation costs [1-9]. Besides this, the PV system needs high investment for the installation of the PV panel. Another resource is the coal-fired (CF) power system that meets our demand for energy through power generation [10]. For example, coming to the real-world scenario, the power production structure in china, more than 70% of the coal power system [11]. However, the CF system inevitably releases $SO_2$, dust, CO, etc. As a result, ozone layer destruction, climate warming, acid rain, air pollution, water pollution, and health risks increase day by day. Also, the government plays another vital role in power generation. The government provides subsidies for the PV power system and the CF power system to protect the environment. With the growing fierce global market competition [12], PV and CF have supported the market environment and meet consumer needs in their interest. As a result, the coexistence of PV and CF turns into a sustainable advantage in the market environment and social life [13].

The evolutionary game theory (EGT) [14] has drawn more attention and has achieved significant development in the past decade. Further, the idea and its application of EGT have been developed rapidly. The more focus of the evolutionary game theory was on the dynamics of strategy (Cooperation or Defection) change as influenced by the various competing systems' in different situations of dilemma game [15-21]. The essence of the dilemma game precisely describes by Tanimoto and Sagara [22] in which they investigated and revealed the idea of GID (gamble-intending dilemma) and RAD (risk-aversion dilemma) to express the social dilemma game [23-29]. Nowadays, evolutionary game theory was widely applied to analyze various gaming behaviors such as firm and industry behaviors, broader biological and dynamical systems, economic growth theory, etc., [30-32] through symmetric and asymmetric games.

In EGT, the symmetric game is a branch of the game in which all the players have the same action, and symmetric payoffs provide in each activity. In contrast, asymmetric games are such types of games in which players do not share their gains equally. Here, different options contract to each player. So, it can be said that the asymmetry games are aroused from the individual differences, phenotype variations such as size, speed, strength, wealth, and environmental variation, based on evolutionary game theory, which is observed in nature. There was substantial development in the study of symmetric games [15-16] that helped promote sustainable development and improved the ecological conditions. Besides, there was a lot of application on asymmetric games, such as parasitic relationships [33], the battle of the sexes [34], animal conflicts [35], and social variation [36-39]. Many researchers had conducted their research and analysis on the behavior of the environment[40-42], pollution [43-45], enterprise [46-50], cyberspace [51], water resources management [52,53], and wind-water system [54], based on the evolutionary game theory.

Research on the application of evolutionary game theory involves cost-benefit-subsidy of the asymmetric games to the environmental issue. Chengrong Pan and Young Long [55] established the game model between the microgrid and conventional grid, concluding that the probability of their positive choice correlates with direct and indirect benefits, government subsidies but reciprocal with costs based on evolutionary game theory. The application of game theory studied in the hybrid energy system between PV and wind [56]. Again, CF used different technology types to power generation based on the analysis of evolutionary game theory [57,58]. The previous studies found that PV and CF game models have rarely been studied based on the evolutionary game analysis. Our research's focus depends on strategy selection in the evolutionary game analysis in terms of the environment. Strategies selection are determined by their decision-making behavior within the entire players [59].

This paper implements the asymmetric evolutionary game models to analyze PV and CF systems' interaction by considering consumer benefits, manufacturers' cost, environmental sustainability, and government subsidy. We have developed two asymmetric game models. First, in Game 1, only cost and benefit for both PV and CF systems are presumed.Both systems compete with each other to keep consumers' maximum benefit and sustainable environment. Next, in Game 2, we assume the cost, benefit, and government subsidy for PV and CF power generation systems. In this context, both systems play with each other for environmental aspects and the government sustainability criteria to get the maximum subsidy. To analyze the effect of interaction, we perform theoretical analysis as well as numerical simulation to show various stability conditions for different parameter variations.

The rest of the paper proceeds as follows: Section 2 introduces the model and method; Section 3 establishes results and discussion; Section 4 is the research conclusion.

## 2. Model

This article focuses on two types of asymmetric games; Game 1 and Game 2. In both games, PV plays with CF for common parameter resources: cost and benefit. However, in Game 2, one additional parameter called "government subsidy" is introduced to meet the sustainable environment given by government.

### 2.1 Game 1

To protect the environment has always been a crucial issue when constructing a power generator system to meet consumers' electricity demand. At first, we presume two players: PV and CF power generator systems on the framework of asymmetric evolutionary game theory. Each player adopts two strategies; either cooperation or defection. Cooperation shows that mutual benefits are exchanged with each other instead of competing. Here, 'cooperation' refers to such behavior in which all necessary equipment and requisite things are prepared and utilized to protect an environment that gets consumer benefit and attention. The term 'benefit' means the income of revenue received through the power industry, whereas 'cost' refers to the spend in which the two players burden environmental provision to attract consumers. Being environmentally-oriented preference, consumers favor choosing that industry based on the environmentally-friendly power generation systems for sustainable development. Although it should be mentioned that the demand level of consumers is flexible, not a fixed value. The interaction between PV and CF power industries with two strategic types, cooperator and defector, can be characterized by a 2 × 2 asymmetric game with the following payoff matrix:

$$\begin{array}{cc} & \boldsymbol{CF\ (C)} \qquad\qquad \boldsymbol{CF\ (D)} \\ \begin{array}{c}\boldsymbol{PV\ (C)}\\ \boldsymbol{PV\ (D)}\end{array} & \begin{pmatrix} B_p - C_p,\ B_c - C_c & \dfrac{B_p}{2} - C_p, \dfrac{B_c}{2} \\ \dfrac{B_p}{2}, \dfrac{B_c}{2} - C_c & 0, 0 \end{pmatrix} \end{array} \quad (1)$$

In this game, if both PV and CF cooperate in maintaining environmental sustainability, they spend the cost, $(C_p, C_c)$, and both receive the benefit $(B_p, B_c)$ of being able to attract consumers. If both game players defect, each pays no cost and receives no benefit. Thus, Game 1 can be explained as follows:

a) PV and CF, both cooperate: If both systems cooperate, consumers notice that both power generators pay their maximum effort to protect the environment. Therefore, two power industries will get benefit $(B_p, B_c)$ from consumers and spend the costs $(C_p, C_c)$ related to the electric power to meet environmental sustainability ($B_p$= benefit of PV, $B_c$= benefit of CF, $C_p$= cost of PV and $C_c$= cost of CF ). Here, $x$ and $y$ represent the frequencies of cooperation for PV and CF, respectively. However, $1-x$ and $1-y$ denote for the frequencies of defection for PV and CF. Here, $(0 \le x \le 1, 0 \le y \le 1)$.

b) PV and CF, both defect: If both power generator industries do not pay any attention to protect the environment, the consumers do not purchase any power from those two players. Therefore, both players obtain none of the benefits and pay no cost.

c)PV cooperates but CF defects and vice versa: If PV cooperates and CF defects, then PV is wished to pay the cost $C_p$; in contrast, CF is requested to pay the cost $C_c$, when CF cooperates and PV defects. Meanwhile, both systems share the benefit, $(B_p, B_c)$, equally. This implies that if one of the power systems pay attention to reduce the environmental problem, consumers will see what happened in those two industries. For example, when one of the power generator industry (PV or CF) cooperates and another one defects, the consumer consumes electric power from both systems. Thus, PV and CF share the benefits equally; denoted by $\frac{B_p}{2}$ and $\frac{B_c}{2}$, respectively. Consumers inherently know that one of the power generators does not pay attention to a sustainable environment; however, another pay effort by spending cost.

### 2.1.1 Result and discussion for game 1

Here we develop a framework for game 1 for two power generator systems: PV and CF on the framework of asymmetric games in which the payoffs depend on the cost, benefit, and subsidy of the players as well as their strategies. We perform both analytical and numerical analysis to show the interaction between two systems and their corresponding varying parameters.

#### 2.1.1.1 Analytical approach for game 1

In the framework of Game 1 (equation 1), if $x$ and $y$ represent the cooperation fraction of PV and CF, respectively, then the replicator equation can be expressed as follows (see appendix),

$$\frac{dy}{dt} = y(1-y)(\frac{B_p}{2} - C_p) \qquad (2)$$

$$\frac{dx}{dt} = x(1-x)\left(\frac{B_c}{2} - C_c\right) \qquad (3)$$

According to the stability criteria of the Jacobian matrix (see appendix), when *dx/dt=0* and *dy/dt=0* , we obtained four equilibria as $(x,y) = (0,0), (0,1), (1,1)$ and $(1,0)$. The equilibria and corresponding ESS (evolutionarily stable strategy) are summarized in Table 1. Also, the phase portrayed is displayed in figure 1 for four equilibrium points.

From Table 1, we observe four equilibrium points and corresponding stability conditions (ESS, saddle and unstable). Consequently, fig. 1 presents four equilibria for various conditions, such as, $C_p > B_p/2$,$C_c > B_c/2$, (b) $C_p > B_p/2, C_c < B_c/2$ (c) $C_p < B_p/2$, $C_c > B_c/2$ and (d) $C_p < B_p/2$, $C_c < B_c/2$ along PV and CF. Here, O, A, B, and C show the equilibria points (0,0), (0,1), (1,1) and (1,0), respectively. Detailed of the evolutionary mechanism and stability conditions for Game 1 is described as follows,

a) When $C_p > B_p/2$, $C_c > B_c/2$ (i.e., when the cost of PV is greater than the benefit of PV then this condition adopts cooperation strategy. Again, the cost of CF is greater than its benefit then this condition supports cooperation strategy), there are four equilibrium points in the system (Table 1), and it can be inferred from Fig.1(a). Both parties adopting defective strategy is an evolutionary stable strategy (ESS), as the system converges to O (0,0) (shown in Fig. 1(a)).

b)When $C_p > B_p/2, C_c < B_c/2$ (i.e., the cost of PV is greater than its benefit then it adopts cooperation strategy, again, when the cost of the CF is less than its benefit then it adopts cooperation strategy), there are four equilibrium points in the system which converges to C(1,0),as seen from Table 1 and Fig. 1(b).It suggests that PV adopts cooperative strategy and CF chooses the defection strategy ,this point is called as an ESS point.

c)When $C_p < B_p/2$, $C_c > B_c/2$ (i.e., while the cost of PV is less than its benefit, it adopts cooperation strategy, the cost of the CF is greater than its benefit then it adopts cooperation strategy), there are four equilibrium points in the system which converges to A(0,1),as seen from Table 1 and Fig. 1(c). It suggests that CF chooses cooperative strategy and the PV adopts the defection strategy, this equilibrium point is as ESS point.

d)When $C_p < B_p/2$, $C_c < B_c/2$ (i.e.,the cost of PV is less than its benefit when it adopts cooperation strategy, the cost of the CF is less than its benefit when it adopts cooperation strategy), there are four equilibrium points in the system which converges to B(1,1),as seen from Table 1 and Fig.1(d). It suggests that cooperative strategy for both parties is actually an ESS point.

Backing to the definition of payoff matrix Game 1, we could note that the results as above; both analytical and numerical, could be consistent with the combination of signs of $\frac{B_p}{2} - C_p$ (the third brackets of Eq. (3)) and $\frac{B_c}{2} - C_c$ (the third brackets of Eq. (4)). Yet, it would be meaningful to explicitly note the condition bringing ESS and to show numerical examples as above.

#### 2.1.1.2 Numerical approach for game 1

To validate our theoretical simulation (Fig. 1) by using deterministic method to determine numerical analysis. Numerical simulation is carried out through C/C++ programming to make an in-depth analysis of the evolution of cooperation between PV and CF power system under four cases. The horizontal and vertical axis show the different initial conditions$x(0)$ and $y(0)$ with respect to time. We presume for PV and CF system are (Fig. 2);

$a)C_p = 0.5$ , $B_p = 0.6$ , $C_c = 0.5$ , $B_c = 0.7$ ($C_p > B_p/2$, $C_c > B_c/2$ )**:** This condition will converge to 0 for both, PV and CF (Fig. 2(a)). At this situation, PV and CF tends to present defection to generate the electricity.

Table 1. Stability of local equilibrium points for different condition for Game 1.

| **Equilibrium points** $(x, y)$ | $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$ | $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$ | $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ | $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ |
|---|---|---|---|---|
| (0,0) | $-,-$ **(ESS)** | $-,+$ (Saddle) | $+,-$ (Saddle) | $+,+$ (Unstable) |
| (0,1) | $+,-$ (Saddle) | $+,+$ (Unstable) | $-,-$ **(ESS)** | $-,+$ (Saddle) |
| (1,0) | $-,+$ (Saddle) | $-,-$ (ESS) | $+,+$ (Unstable) | $+,-$ (Saddle) |
| (1,1) | $+,+$ (Unstable) | $+,-$ (Saddle) | $-,+$ (Saddle) | $-,-$ **(ESS)** |

$b) C_p = 0.3$ , $B_p = 0.4$ , $C_c = 0.2$ , $B_c = 0.5$ ($C_p > B_p/2$, $C_c < B_c/2$)**:** This system will toward point to 1 for PV and 0 for CF (Fig. 2(b)). Thus, this result shows that the tendency of PV allows the cooperation, while CF represents the defection to produce electricity.

$c) C_p = 0.2$ , $B_p = 0.5$ , $C_c = 0.3$ , $B_c = 0.4$ ($C_p < B_p/2$, $C_c > B_c/2$)**:** This assumed parameters will meet to 0 for PV and 1 for CF (Fig. 2(c)). This situation presents cooperation for CF whereas PV is in reverse strategy.

$d) C_p = 0.2$ , $B_p = 0.5$ , $C_c = 0.2$ , $B_c = 0.5$ ($C_p < B_p/2$, $C_c < B_c/2$): This condition will support 1 for PV and CF both (Fig. 2(d)). Both resources provide cooperation to generating electricity.

### 2.2 Game 2

In Game 1, it was modeled that the PV and CF power generation system under asymmetric EGT has been considered cost and benefit, which often depends on consumers' interest and environment issue. Thus, it is constructive to introduce government subsidy or reward based on sustainable environment preference. If the government declares the subsidy or reward package for power industries to keep eco-friendly power generation systems for sustainable development, then formulate 2 × 2 asymmetric games (Game 2) as,

$$\begin{array}{c} \\ \boldsymbol{PV\ (C)} \\ \boldsymbol{PV\ (D)} \end{array} \begin{array}{c} \boldsymbol{CF\ (C)} \qquad\qquad \boldsymbol{CF\ (D)} \\ \begin{pmatrix} \frac{B_p}{2}+\frac{S}{2}, \frac{B_c}{2}+\frac{S}{2} & 0, B_c+S \\ B_p+S, 0 & \frac{B_p}{2}-C_p, \frac{B_c}{2}-C_c \end{pmatrix} \end{array} \quad (4)$$

According to the game, there are two game players (PV and CF) and two external players as consumers and the government. The government provides subsidies for the power industry to protect the environment. Therefore, if both PV and CF cooperate, they support each other and shared the benefit and the government allowance equally. However, both pay the cost to attract consumers and not get any subsidy from authorities when both defects. Game 2 can be summarized as follows:

a) PV and CF, both cooperate: If both players cooperate to protect the environment, they shared their benefits and subsidies equally, *($B_p/2 + S/2$)*.

b) PV and CF, both defect: If both two players do not agree to cooperate to protect the environment, the government imposes some fine or rules to maintain the environmental sustainability. As a result, additional costs termed as $C_p$ and $C_c$ are required, which can be regarded as a government penalty. Thus, if both players defect bring a worse situation for the consumer as well as the government side.

c) PV cooperates and CF defects or vice versa: If one player adopts to cooperate and other agree to defect, the co-operator helps the defector sacrifice both benefit and subsidy. In this situation, PV decides to give his entire allowance and benefit to CF due to a very altruistic mind to save the environment.

#### 2.2.1 Result and discussion for game 2

Both analytical and numerical analysis are done for game 2 to present the interaction between two systems and their corresponding parameters regarding two power generator systems: PV and CF.

##### 2.2.1.1 Analytical approach for game 2

The evolutionary game model for PV and CF, describes the progressive process for the transformation of both sides favorable strategy. Both sides are not adjusting their strategies at the same time. One side needs to decide its strategy by considering the other side's strategy and the payoff the strategy brings. From the evolutionary game theory's perspective, the payoff matrix in the gaming can be expressed as shown in equation 4.

Based on these, if PV and coal both choose cooperation strategy, the replicator dynamics differential equation (variant with time) is (see appendix)

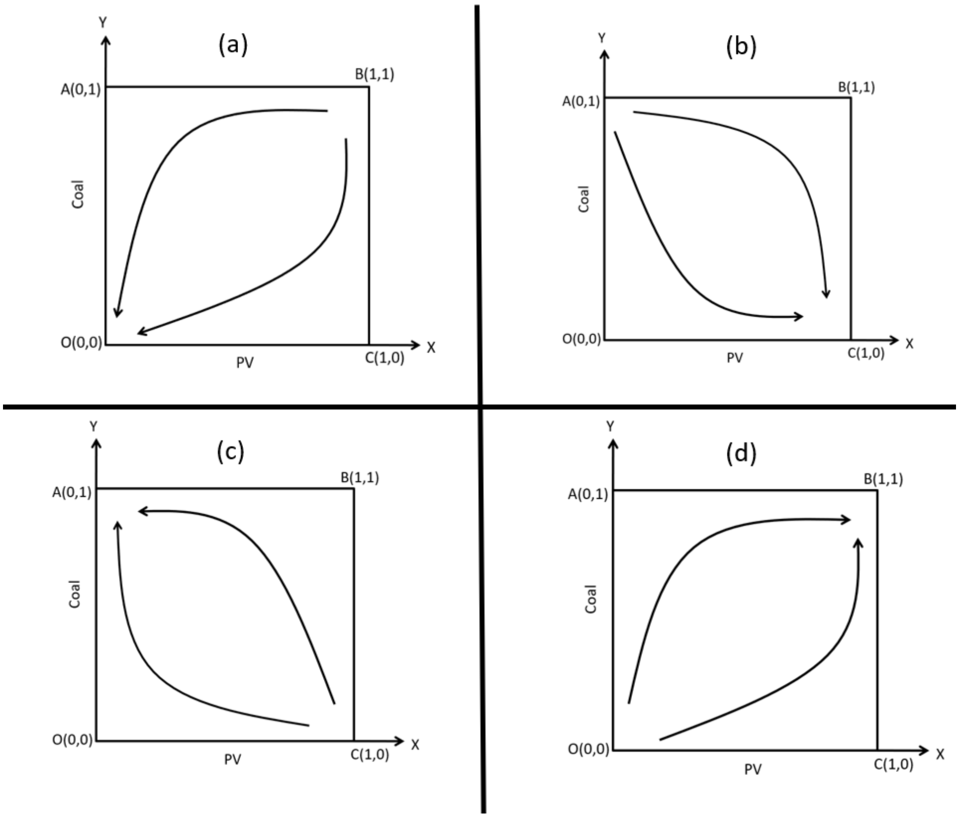


**Fig. 1**: Schematic diagram of dynamic evolution for different conditions; (a) $C_p > B_p/2$, $C_c > B_c/2$ , (b) $C_p > B_p/2$, $C_c < B_c/2$ , (c) $C_p < B_p/2$, $C_c > B_c/2$ and (d) $C_p < B_p/2$, $C_c < B_c/2$ for figs. (a), (b), (c) and (d), respectivel

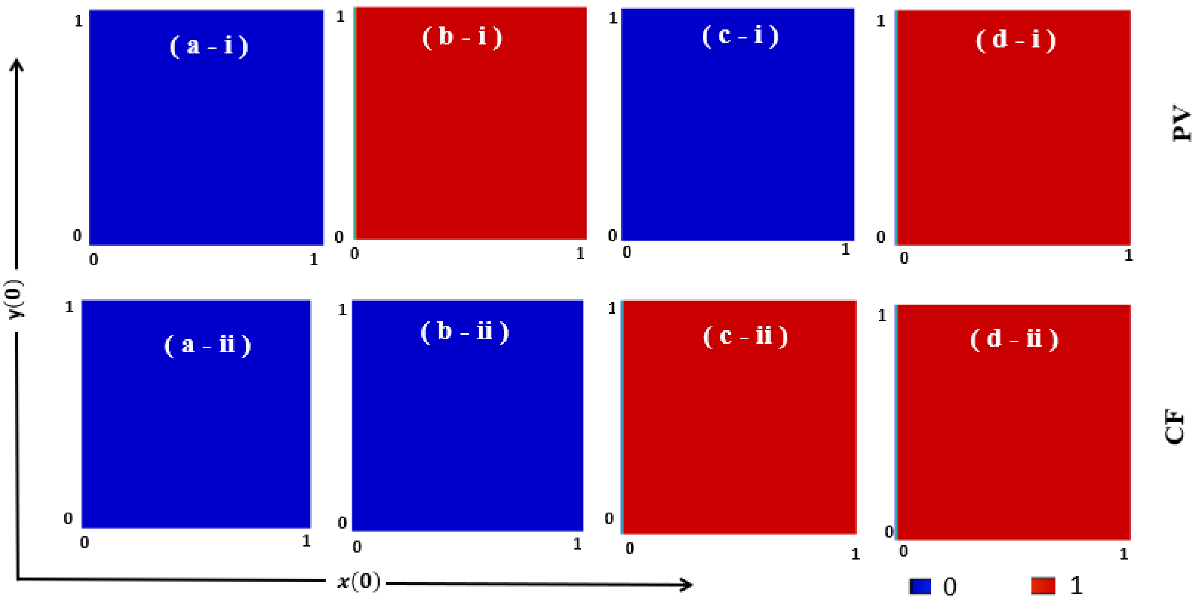


**Fig. 2**: Evolutionary different game phase diagram of PV $(* - i)$ and coal $(* - ii)$ system; (a) $C_p = 0.5$ , $B_p = 0.6$ , $C_c = 0.5$ , $B_c = 0.7$ ( $C_p > B_p/2$, $C_c > B_c/2$ **),** (b)$C_p = 0.3$ , $B_p = 0.4$ , $C_c = 0.2$ , $B_c = 0.5$ ( $C_p > B_p/2$, $C_c < B_c/2$**)** , (c) $C_p = 0.2$ , $B_p = 0.5$ , $C_c = 0.3$ , $B_c = 0.4$ ($C_p < B_p/2$, $C_c > B_c/2$ ) and (d) $C_p = 0.2$ , $B_p = 0.5$ , $C_c = 0.2$ , $B_c = 0.5$ ($C_p < B_p/2$, $C_c < B_c/2$ **).**

$$\frac{dy}{dt} = y(y-1)(x\left(\frac{S}{2}+C_p\right)+\frac{B_p}{2}-C_p) \quad (5)$$

$$\frac{dx}{dt} = x(x-1)(y\left(\frac{S}{2}+C_C\right)+\frac{B_C}{2}-C_C) \quad (6)$$

According to the evolutionary stability condition of the Jacobian matrix (see appendix), when $dy/dt=0$, $dx/dt=0$ ,there are the five equilibrium points that can be found as $O(0,0), A(0,1), B(1,1)$, $C(1,0)$ and $E(x^*,y^*)$. From equation (A17) and (A18), the evolutionary strategy matrix concerning between PV and CF is conducted. The equilibrium stability point of the evolution system can be found by analyzing the stability of Jacobian matrix of the system. The Jacobian matrix is expressed as in equation (A19). The equilibrium stability points are obtained (Table 2) from the equation (A24-A31) (see appendix). Detailed analysis of the evolutionary game is described as follows.

a)When $C_p > B_p/2$, $C_c > B_c/2$, $S > 0$ (i.e., the cost of PV is greater than its benefit when it adopts cooperative strategy, while the cost of CF is greater than its benefit then it chooses cooperative strategy, the government subsidy is positive), According to the Fig.3(a) and Table 2, A and C are in evolutionary steady-state (ESS), O and B are unstable points, and E is a saddle point. At that situation, the initial state reaches in the upper left area of the system formed by $OABE$, the system converges to the $A(0,1)$. That is to say, CF adopts cooperation strategy and PV chooses non-cooperative strategy, the system goes to stable confrontation state as $A(0,1)$. Again, when the initial states fall in the bottom right area of the system formed by the $OCBE$ ,the system reaches to $C(1,0)$,that means, PV chooses cooperative strategy and CF chooses defective strategy, as a result, $C(1,0)$ shows a stable confrontation state.

b)When $C_p > B_p/2$, $C_c < B_c/2$, $S > 0$ (i.e., the cost of PV is greater than its benefit when it chooses cooperative strategy, while the cost of CF is less than its subsidy when it adopts cooperative strategy, the government subsidy is positive), there are equilibrium points in which meets to A(0,1),as seen from Table 2 and Fig. 3(b).It suggests that PV adopts defective strategy and CF chooses the cooperative strategy, the system is an ESS.

c)When $C_p < B_p/2$, $C_c > B_c/2$, $S > 0$ (i.e., the cost of PV is less than its benefit when it adopts cooperative strategy, while the cost of CF is greater than its subsidy when it adopts cooperative strategy, the government subsidy is positive), there are equilibrium points in the system which converges to C(1,0), as seen from Table 2 and Fig.3(c). It suggests that PV chooses cooperative strategy and CF adopts the defective strategy, the system is an ESS point.

d)When $C_p < B_p/2$, $C_c < B_c/2$, $S > 0$ (i.e., the cost of PV is less than its benefit when it adopts cooperative strategy, while the cost of CF is less than its subsidy when it adopts cooperative strategy, the government subsidy is positive), there are equilibrium points in the system which converges to O(0,0), as seen from Table 2 and Fig. 3(d). It suggests that both parties adopt defective strategy.

### 2.2.1.2 Numerical approach for game 2

As we did as above, the horizontal and vertical axis show the different initial conditions $x(0)$ and $y(0)$ with respect to time. We presume different conditions for PV and CF system are (Fig. 3);

*a)* $C_p > B_p/2$, $C_c > B_c/2$, $S > 0$: Through the condition $C_p > B_p/2$, $C_c > B_c/2$, $S > 0$, we have done several analyses. (i)When the subsidy, S is increased:

All these setting parameters (i.e., $C_p = B_p = C_c = B_c = \mathrm{S} = 0.5$ ) other than subsidy, S (i.e. 1, 3 and 10) is symmetric. So, there is no difference on the structure of equal size of the basin for those two players (Fig. 4).

(ii)Changing the cost of PV, $C_p$:

We varied $C_p$. With respect to $C_p$, there is some sorts of inequality comes up as compared with $C_c$. If we back to the case of $C_p$=0.5 and other parameters $B_p = C_c = B_c = 0.5$ and $S = 1$ which recovers totally symmetric case (Fig. 5(a)). So perfectly gridline appears again in which equal basins appearing for both two players PV and CF. If we increase the magnitude only for PV in skewed manner which implies $C_p$= 0.8, because of this, basin of PV decreases like Fig. 5(c). In contrast, if we consider $C_p$ = 0.3 the basin of PV increases like Fig. 5 (b).

(iii)Changing the benefit of coal, $B_c$ :

We changed the magnitude of $B_c$. After varying $B_c$, we found some sorts of inequality comes up as compared with $B_p$. If we adopt the case of $B_c$= 0.5 and other parameters $B_p = C_c = B_c = 0.5$ and $S = 1$ which shows totally a symmetric case (Fig. 6(a)). So, both two players PV and CF show perfectly equal basin. If the benefit only for coal is increased in skewed manner which implies that $B_c$=0.9, because of this, basin of PV decreases like Fig. 6(c). On the contrary, if we presume $B_c$=0.2 then the basin of PV increases like Fig. 6 (b).

In those comparisons (Figs. 4 to 6), one may think that why a so-called internal equilibrium does not appear. Let us reference to Fig. 5 (c) again for instance. By consulting with the concept of universal dilemma strength[1- 32)], we can confirm that both Chicken-type dilemma strengths, or GIDs, are positive; $D_g|_{PV} = (B_p + S) - (B_p/2 + S/2) = B_p/2 + S/2 > 0$ and $D_g|_{CF} = (B_c + S) - (B_c/2 + S/2) = B_c/2 + S/2 > 0$, whereas both Stag Hunt-type dilemma strengths, or RADs, are negative; $D_r|_{PV} = (B_p/2 - C_p)-0 = 0.5/2 - 0.8<0$ and $D_r|_{CF} = (Bc/2 - C_c)-0 = 0.5/2 - 0.5<0$. Because of this numeric evaluation, one may expect to observe an internal equilibrium like what can be in a symmetric Chicken game. But we could not see such tendency at all in Fig. 5 (c). The observed equilibrium is, instead of polymorphic, bi-stable; either $(x,y) = (1,0)$ (denoted by 'PV' indicating PV to fully

Table 2. Stability of local equilibrium points for different condition for game 2.

| **Equilibrium point** $(x, y)$ | $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$ | $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$ | $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ | $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ |
|---|---|---|---|---|
| (0,0) | $+,+$ (Unstable) | $+,-$ (Saddle) | $-,+$ (Saddle) | $-,-$ **(ESS)** |
| (0,1) | $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$ | $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$ | $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}, S > 0$ | $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}, S > 0$ |
| | $-,-$ **(ESS)** | $-,-$ **(ESS)** | $-,+$ (Saddle) | $-,+$ (Saddle) |
| (1,0) | $-,-$ **(ESS)** | $+,-$ (Saddle) | $-,-$ **(ESS)** | (Saddle) |
| (1, 1) | $+,+$ (Unstable) | $+,+$ (Unstable) | $+,+$ (Unstable) | $+,+$ (Unstable) |
| $\left(\frac{C_p - \frac{B_p}{2}}{C_p + \frac{S}{2}}, \frac{C_c - \frac{B_c}{2}}{C_c + \frac{S}{2}}\right)$ | $C_p > \frac{B_p}{2}, C_c > \frac{B_c}{2}$ | $C_p > \frac{B_p}{2}, C_c < \frac{B_c}{2}$ | $C_p < \frac{B_p}{2}, C_c > \frac{B_c}{2}$ | $C_p < \frac{B_p}{2}, C_c < \frac{B_c}{2}$ |
| | $+,-$ (Saddle) | $+,-$ (Saddle) | $-,+$ (Saddle) | $-,+$ (Saddle) |

cooperative; while CF to fully defective), or $(0,1)$ (denoted by "CF' indicating CF to be fully cooperative). This is because, unlike a symmetric game where quite strong constraint; $x + y = 1$ , is imposed, in an asymmetric game like the current model presuming, $x$ and $y$ independently range [0,1], which loses the attraction by internal equilibrium as above and leads to appear a bi-stable equilibrium as we could observe. This is quite common in such an asymmetric game, although most of the previous studies have missed out to discuss.

*b)* $C_p > B_p/2, C_c < B_c/2, S > 0$: We presumed the value as; $C_p = 0.2$ , $B_p = 0.2$ , $C_c = 0.2, B_c = 0.2, S = 0.5$ . This condition supports 0 for PV and 1 for CF (Fig.7(a)). This result shows the tendency of PV adopts defection strategy and CF supports cooperation strategy.

*c)* $C_p < B_p/2, C_c > B_c/2, S > 0$ : We presumed the value as; $C_p = 0.1$ , $B_p = 0.5$ , $C_c = 0.2, B_c = 0.2, S = 0.5$ . This condition converges to 1 for PV and 0 for CF (Fig. 7(b)). This result shows the tendency of PV adopts cooperation strategy and CF supports defection strategy.

*d)* $Cp < Bp / 2, C_c < B_c/2, S > 0$ : We presumed the value as; $C_p = 0.2$ , $B_p = 0.5$ , $C_c = 0.2, B_c = 0.5, S = 0.5$. This condition supports 0 for PV and CF both (Fig. 7(c)). At this situation, PV and CF tend to support defection strategy to generate electricity.

## 3. Conclusion

This study contributes to the power generation system based on evolutionary game theory. According to the evolutionary game theory, two games; game 1 and game 2, are played between two players (PV and CF). Benefits and costs are the presumed parameters for game 1, whereas, in game 2, benefits, costs, and government subsidies are considered for the game players. We explored their impact on evolutionary behavior between PV and CF. As a result, we tried to find out ESS regarding the different conditions of the games. Furthermore, we verified the theoretical results with numerical simulation.

Based on the research results, the paper proposes the following suggestions for game 1.

The strategic choice for power generation by PV and CF is correlated with benefits and costs, shown in our game model. According to the simulation analysis, we find that the costs and benefits have more significant impacts on the evolutionary game approach's evolutionary trend.

Based on the research, our paper proposes the following recommendations for game 2.

According to the game model analysis based on evolutionary game theory, government subsidies are useful for motivating power generation. If the government subsidies are increased, then an equal share will be distributed. When the cost of PV is higher than that of CF, so, the consumers tendency will go for CF system to

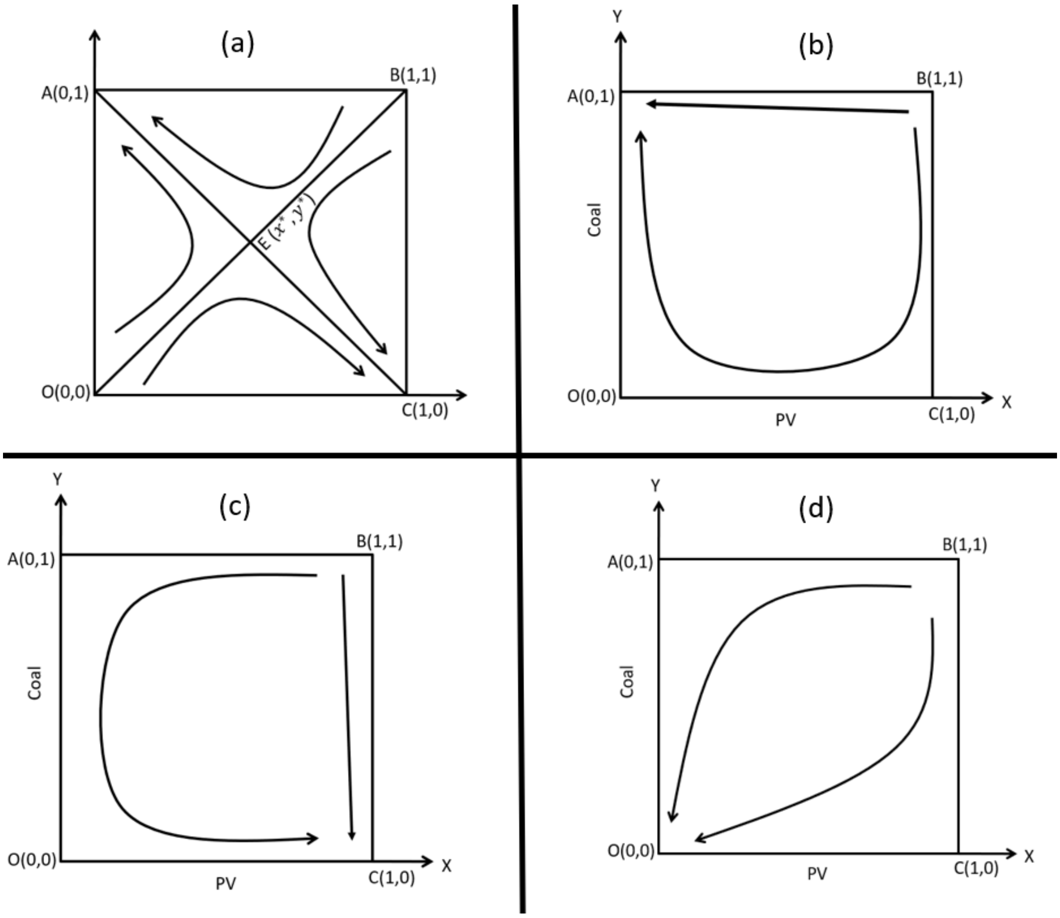


**Fig. 3**: Schematic diagram of dynamic evolution for different conditions; (a)$C_p > B_p/2, C_c > B_c/2, S > 0$ (b)$C_p > B_p/2, C_c < B_c/2, S > 0$ (c) $C_p < B_p/2, C_c > B_c/2, S > 0$ and (d) $C_p < B_p/2, C_c < B_c/2, S > 0$ for fig. (a), (b), (c) and (d), respectively.

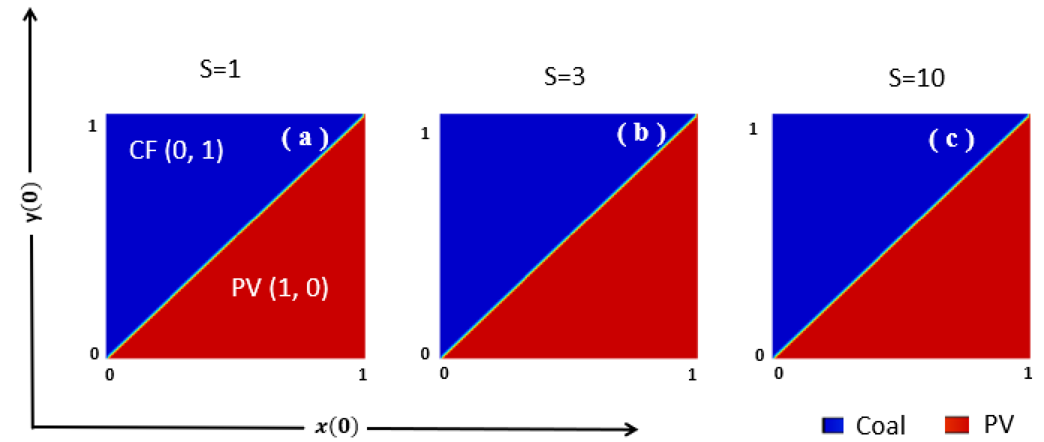


**Fig. 4**: Phase diagram of the evolutionary game analysis between PV and coal; (a) $C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1$ (b) $C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 3$ (c) $C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 10$.

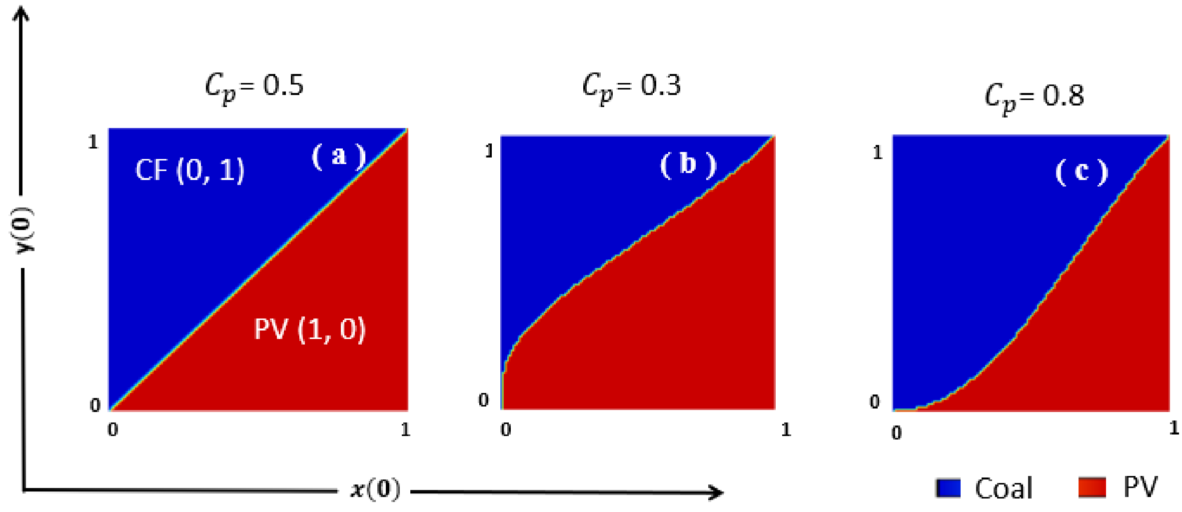


**Fig. 5**: Phase diagram of Evolutionary game analysis between PV and coal; (a) $C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$ (b)$C_p = 0.3, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$ (c) $C_p = 0.8, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$.

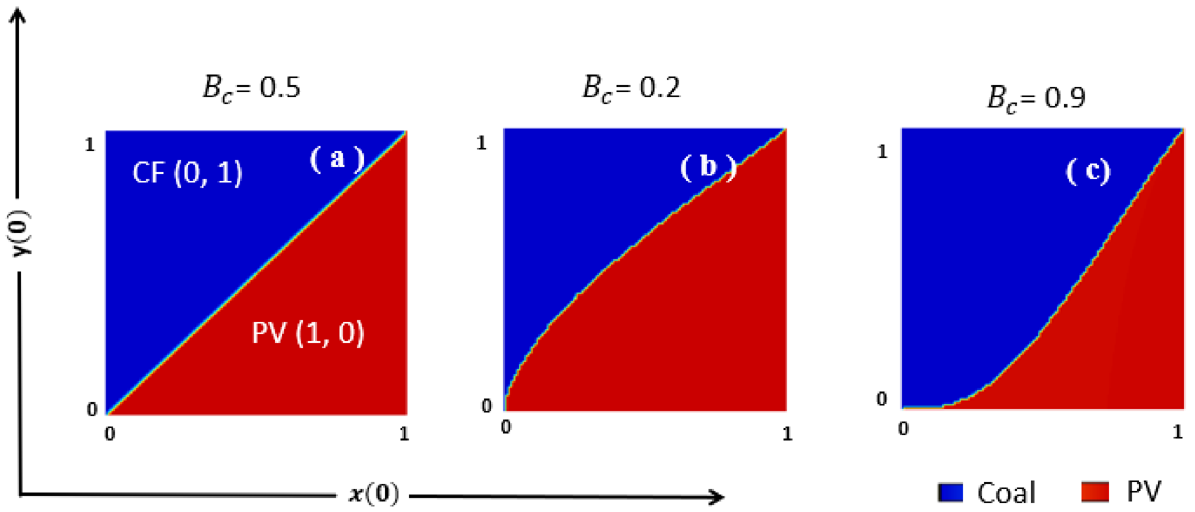


**Fig. 6**: Phase diagram of the evolutionary game for PV and coal system; (a) $C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.5, S = 1.0$ (b)$C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.2, S = 1.0$ (c)$C_p = 0.5, B_p = 0.5, C_c = 0.5, B_c = 0.9, S = 1.0$ .

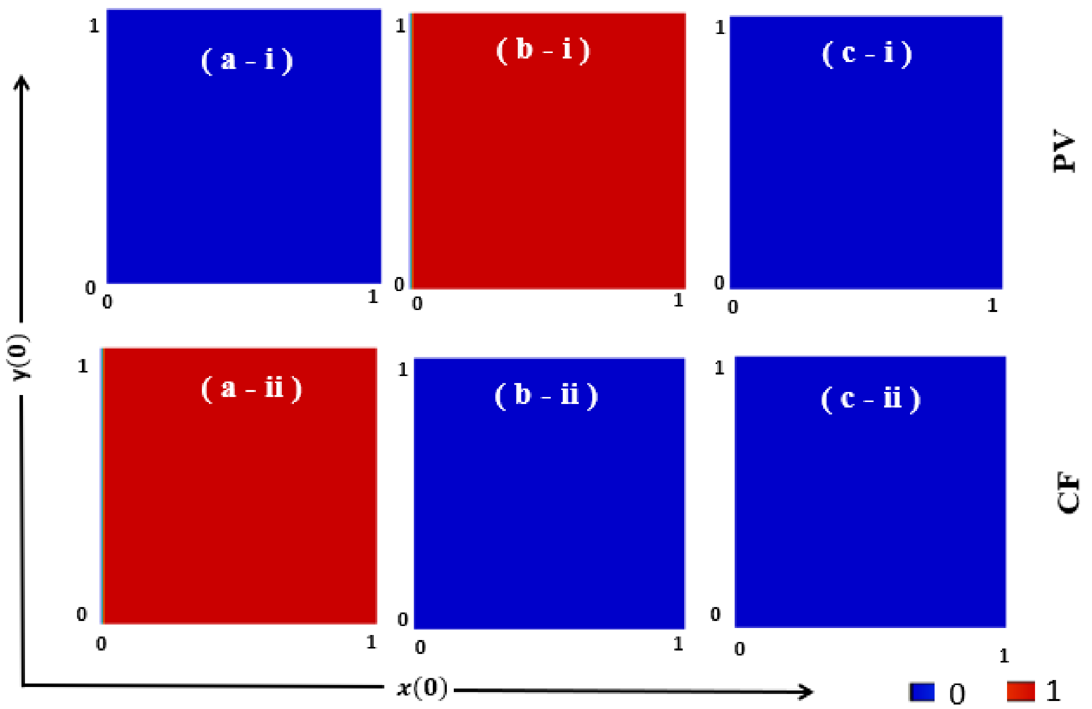


**Fig. 7**: Evolutionary different game phase diagram of PV $(* - i)$ and coal $(* - ii)$ system; (a) $C_p = 0.2$, $B_p = 0.2$, $C_c = 0.2$, $B_c = 0.2$, $S = 0.5$ $(C_p > B_p/2, C_c < B_c/2, S > 0)$, (b)$C_p = 0.1$, $B_p = 0.5$, $C_c = 0.2$, $B_c = 0.2$, $S = 0.5$ $(C_p < B_p/2, C_c > B_c/2, S > 0)$ and (c) $C_p = 0.2$, $B_p = 0.5$, $C_c = 0.2$, $B_c = 0.5$, $S = 0.5$$(C_p < B_p/2, C_c < B_c/2, S > 0)$.

purchase the power. That means the cooperation rate of CF is higher. Furthermore, as CF's benefit is deceased, it becomes lower than that of a PV system, meaning the CF system's has lower cooperation rate to power generation system.

## References

1) L. L Kazmerski, "Photovoltaics R & D: At the Tipping Point," NREL/CP-520-37553, January,2005.https://www.nrel.gov/docs/fy05osti/37553.pdf.
2) G.K.Singh, "Solar power generation by PV (photovoltaic) technology: A review" *Energy*, **53** 1-13(2013). doi: 10.1016/j.energy.2013.02.057.
3) M. M. Rahman, M. M.H. Khan, M. A. Ullah, and X. Zhang, A. Kumar. "A hybrid renewable energy system for a North American off-grid community," *Energy*, **97** 151-160 (2016). doi: 10.1016/j.energy.2015.12.105.
4) S. S. Mendu, P. Appikonda, A. K. Emadabathuni, and N. Koritala, "Techno-economic comparative analysis between grid-connected and stand-alone integrated energy systems for an educational institute," *Evergreen* **7**, 382–395 (2020). doi: 10.5109/4068616.
5) R. A. Rouf, M. A. Hakim Khan, K. M. Ariful Kabir, and B. B. Saha, "Energy management and heat storage for solar adsorption cooling," *Evergreen* **3**, 1–10 (2016). doi: 10.5109/1800866
6) I. Roihan, K. Tjandaputra A., E. A. Setiawan, and R. A. Koestoer, "Installing and testing the grash of portable incubator powered using the solar box 'be-care' for remote areas without electricity," *Evergreen* **7**, 621–628 (2020). doi: 10.5109/4150516.
7) K. Marzia, M. F. Hasan, T. Miyazaki, B. B. Saha, and S. Koyama, "Key factors of solar energy progress in Bangladesh until 2017," *Evergreen* **5**, 78–85 (2018). doi: 10.5109/1936220.
8) P. Pal, A. K. Nayak, and R. Dev, "A modified double slope basin type solar distiller: Experimental and enviro-economic study," *Evergreen* **5**, 52–61 (2018). doi: 10.5109/1929730.
9) Y. D. Kim, K. Thu, and K. C. Ng, "Evaluation and parametric optimization of the thermal performance and cost effectiveness of active-indirect solar hot water plants," *Evergreen* **2**, 50–60 (2015). doi: 10.5109/1544080.
10) A. Wahid, D. R. Mustafida, and Y. A. Husnil, "Exergy analysis of coal-fired power plants in ultra supercritical technology versus integrated gasification combined cycle," *Evergreen* **7**, 32–42 (2020). doi: 10.5109/2740939.
11) Y. Huang, H. Wang, and S. Liu, "Research on 'near-zero emission' technological innovation diffusion based on co-evolutionary game approach," *Syst. Sci.*

*Control Eng.*, **7***(2)* 23–31 (2019).doi.org/10.1080/21642583.2019.1620657.
12) T. Fujisaki, "Evaluation of Green Paradox: Case Study of Japan," *Evergreen* **5**, 26–31 (2018). doi: 10.5109/2174855.
13) J.Bushnell, A.,Halseth, E. G.Read, and J. S. Rogers, "An International Comparison of Models for Measuring Market Power in Electricity," *Manage. Sci*., 1 (1999) . https://web.stanford.edu/group/emf-research/docs/emf17/EMF17.1.pdf.
14) P. D. Taylor, and L. B. Jonker "Evolutionary stable strategies and game dynamics," *J. Math. Biosci.*, **40***(1–2)* 145–156 (1978).doi:10.1016/0025-5564(78)90077-9.
15) J. Tanimoto ,"Fundamentals of Evolutionary Game Theory and its Applications," Springer, 2015.
16) J.Tanimoto,"Evolutionary Games with Sociophysics," Springer, 2018.
17) W. B. Du, X. Bin Cao, L. Zhao, and M. Bin Hu, "Evolutionary games on scale-free networks with a preferential selection mechanism," *Phys. A Stat. Mech. its Appl.*, **388***(20),* 4509–4514 (2009).doi:10.1016/j.physa.2009.07.012.
18) M.A.Habib, K. M. A. Kabir,and J. Tanimoto, "Do humans play according to the game theory when facing the social dilemma situation?' A survey study," *Evergreen*, **7***(*1) 7–14 (2020). doi: 10.5109/2740936.
19) H.Ito,Y.Katsumata,E.Hasegawa, and J. Yoshimura, "The promotion of cooperation by the poor in dynamic chicken games," *Sci. Rep.*, **7**, 1–10 (2017). doi:10.1038/srep43377.
20) M.A.Habib, M.Tanaka, and J.Tanimoto, "How does conformity promote the enhancement of cooperation in the network reciprocity in spatial prisoner's dilemma games?," *Chaos, Solitons and Fractals,* **138**, 1-7 (2020).doi:10.1016/j.chaos.2020.109997.
21) Berg, D., Weissing, J. F.; "Evolutionary Game Theory and Personality," *Evol. Psychol.*, **May** 451-463 (2015).doi:10.1007/978-3-319-12697-5_34.
22) J.Tanimoto, and H. Sagara, "Relationship between dilemma occurrence and the existence of a weakly dominant strategy in a two-player symmetric game," *BioSystems*, **90** *(1)* 105–114 (2007). doi:10.1016/j.biosystems.2006.07.005.
23) H.Ito, and J. Tanimoto, "Scaling the phase-planes of social dilemma strengths shows game-class changes in the five rules governing the evolution of cooperation," *R. Soc. Open Sci.,* **5** *(10)* 1-9 ( 2018).doi:10.1098/rsos.181085.
24) J.Tanimoto, "Promotion of cooperation by payoff noise in a 2×2 game," *Phys. Rev. E - Stat.* Nonlinear., **76** 041130-7 (2007).doi:10.1103/PhysRevE.76.041130.
25) Z. Wang, S. Kokubo, M. Jusup, and J.Tanimoto, "Universal scaling for the dilemma strength in evolutionary games," *Phys. Life Rev.,* **14** 1–30 ( 2015).doi:10.1016/j.plrev.2015.04.033.
26) J.Tanimoto," Dilemma solving by the coevolution of networks and strategy in a 2×2 game," *Phys. Rev. E - Stat. Nonlinear*, **76** 021126 ( 2007).doi:10.1103/PhysRevE.76.021126.
27) J.Tanimoto,"Coevolutionary,coexisting learning and teaching agents model for prisoner's dilemma games enhancing cooperation with assortative heterogeneous networks," *Phys. A Stat. Mech. It Appl.*, **392** *(13)* 2955–2964 (2013). doi:10.1016/physa.2013.02.004.
28) J.Tanimoto, "Promotion of cooperation through co-evolution of networks and strategy in a 2 × 2 game," *Phys. A Stat. Mech. its Appl.,* **388** *(6)* 953–960 (2009). doi:10.1016/j.physa.2008.11.023.
29) M. Alam, K.Nagashima, and J. Tanimoto, "Various error settings bring different noise-driven effects on network reciprocity in spatial prisoner's dilemma," *Chaos, Solitons and Fractals*, **114** 338–346 (2018).doi:10.1016/j.chaos.2018.07.014.
30) J.Tanimoto,"Mathematical Analysis of Environmental System," Springer, 2014.
31) P. A. David, "Clio and the economics of qwerty," *Am. Econ. Rev.*, **75***(2)* 332–337(1985). https://www.jstor.org/stable/1805621.
32) W.He, "A Dynamic Evolutionary Game Model of Modular Production Network," *Discret. Dyn. Nat Soc.*, **January** 1–9 (2016).doi:10.1155/2016/6425158.
33) J. M.Smith, "Evolution and the theory of the games" Cambridge University Press,1982.
34) J. M. Smith, and J. Hofbauer" The battle of the sexes: a genetic model with limit cycle behavior" *Theoretical Population Biology*, **32** *(1)* 1-14 (1987). doi: 10.1016/0040-5809(87)90035-9.
35) R. Selten, "A note on evolutionary stable strategies in asymmetric animal conflicts." *Journal of Theoretical Biology*, **84***(1)* 93-101(1980). doi: 10.1016/S0022-5193(80)81038-1.
36) P. Hammerstein, "The role of asymmetry in animal contests." *Animal Behavior*, **29***(1)* 193-205 (1981). doi: 10.1016/S0003-3472(81)80166-2.
37) H. Ohtsuki, "Stochastic evolutionary dynamics of bimatrix games." *Journal of Theoretical Biology*, **264***(1)* 136-142(2010). doi:10.1016/j.jtbi.2010.01.016.
38) J. Z. He, Y. Zhao, H. J. Cai, and R. W. Wang,"Spatial games and the maintenance of cooperation in an asymmetric Hawk-Dove game," *Chinese Sci. Bull.*, **58***(18)* 2248–2254(2013). doi:10.1007/s11434-013-5810-6.
39) A.McAvoy, and C. Hauert, "Asymmetric
40) Evolutionary Games," *PLoS Comput. Biol.*, **11***(8)* 1–26 (2015).doi:10.1371/journal.pcbi.1004349.
41) T. Guimaraes, and O. Sato, "Benefits of Environmental Stewardship," *J. Transnatl. Manag. Dev.,* **2***(3)* 1996. doi:10.1300/j130v02n03_05.
42) M. E. Porter,and C.V.Linde, "Green and

Competitive : Ending the Stalemate Green and Competitive," *Harv. Bus. Rev.*, **73***(5)* 120–134 (1995).
43) C.Hauert, C.Saade, and A.McAvoy, "Asymmetric evolutionary games with environmental Feedback, "*Journal of Theoretical Biology* ,**462** 347-360(2019). doi:10.1016/j.jtbi.2018.11.019.
44) Y.Wang, and F.Wang, "Evolutionary Game Analysis on Production and Emissions Reduction of Manufacturing Enterprises under Different Carbon Policies," *IOP Conf. Ser. Earth Environ. Sci.*, **199***(2)* 2018.
45) C.Wang, and F. Shi, "An evolutionary game model for industrial pollution management under two punishment mechanisms," *Int. J. Environ. Res. Public Health*, **16***(15)* 2019.doi:10.3390/ijerph16152775.
46) G. Zhu, G. Pan, and W. Zhang, "Evolutionary game theoretic analysis of low carbon investment in supply chains under governmental subsidies," *Int. J. Environ. Res. Public Health,* **15***(11)* 2018.doi:10.3390/ijerph15112465.
47) Q. H. Zhu, and Y. J. Dou,"Evolutionary model between governments and core-enterprises in green supply chains*," Xitong Gongcheng Lilun yu Shijian/System Eng. Theory Pract.*, **27***(12)* .85–89( 2007). doi:10.1016/S1874-8651(08)60075-7.
48) X.Chao,and Z. Zongfang, "The evolutionary game analysis of credit behavior of SME in guaranteed loans organization," *Procedia Comput. Sci.*, **17** 930–938(2013). doi:10.1016/j.procs.2013.05.118.
49) P. Ji, X. Ma, and G. Li, "Developing green purchasing relationships for the manufacturing industry: An evolutionary game theory perspective," *Int. J. Prod. Econ.*, **166** 155–162 (2015). doi:10.1016/j.ijpe.2014.10.009.
50) Z. Li, G. Jin, and S. Duan, "Evolutionary Game Dynamics for Financial Risk Decision-Making in Global Supply Chain," *Complexity,* 2018 2018. doi:10.1155/2018/9034658.
51) C. Hao, Q. Du, , Huang, Y., Shao, L., Yan, Y.; "Evolutionary game analysis on knowledge-sharing behavior in the construction supply chain," *Sustain. ,MDPI*, **11***(19)*, 5319 (2019).doi:10.3390/su11195319.
52) Z. Jianya, L. Weigang, and D. L. Li, "A game-theory based model for analyzing e-marketplace competition," *ICEIS 2015 - 17th Int. Conf. Enterp. Inf. Syst. Proc.*, **1** 650–657(2015).
53) K. Madani, "Game theory and water resources," *J. Hydrol.*, **381** 225–238 (2010). doi:10.1016/j.jhydrol.2009.11.045.
54) Y. Mei, B. Yang, , J. Yang, and T. Wu, "Evolutionary game analysis of water resources conflict for cascade hydropower stations in multiple power generation subjects," *Int. Conf. Logist. Eng. Manag. Comput. Sci. LEMCS 2014*, 947–951(2014).
55) C. M. García Mazo, Y. Olaya, and S. Botero, "Investment in renewable energy considering game theory and wind-hydro diversification," *Energy Strateg. Rev.*, *28* 100447(2020). doi:10.1016/j.esr.2020.100447.
56) C. Pan, and Y. Long, "Evolutionary Game Analysis of Cooperation between Microgrid and Conventional Grid," *Math. Probl. Eng.,* 2015. doi:10.1155/2015/103206.
57) V. Khare, S. Nema, and P. Baredar, "Application of Game Theory in PV-Wind Hybrid System," *Int. J. Electr. Electron. Eng. Res.,* **2***(4)* 25–32(2012).
58) B. Davidson, "Clean coal technologies for electricity generation," *Power Engineering Journal,* **7***(6)*, 257–263 (1993). doi:10.1179/174892408X373464.
59) T.J.Ratajczak, and M.Shahidehpour, "Emerging technology for coal-fired generation," *in Power Engineering Society General Meeting 2006. IEEE*, 2006.
60) B. R. Koka, R. Madhavan, and J. E. Prescott, "The evolution of interfirm networks: Environmental effects on patterns of network change," *Acad. Manag. Rev.*,**31***(3)* 721–737(2006). doi:10.5465/amr.2006.21318927.

## Appendix

### Game 1

Payoff matrix of game 1

$$\begin{array}{c} \\ \boldsymbol{PV\ (C)} \\ \boldsymbol{PV\ (D)} \end{array} \begin{array}{c} \boldsymbol{CF\ (C)} \qquad\qquad\qquad \boldsymbol{CF\ (D)} \\ \begin{pmatrix} B_p - C_p,\ B_c - C_c & \dfrac{B_p}{2} - C_p, \dfrac{B_c}{2} \\ \dfrac{B_p}{2}, \dfrac{B_c}{2} - C_c & 0,0 \end{pmatrix} \end{array}$$

The benefit for a PV in choosing cooperation strategy is-

$$\Pi_{pc} = x(B_p - C_p) + (1-x)\left(\frac{B_p}{2} - C_p\right)$$

$$= xB_p - xC_p + \frac{B_p}{2} - \mathrm{C_p} - x\frac{B_p}{2} + xC_p$$

$$= x\frac{B_p}{2} + \frac{B_p}{2} - \mathrm{C_p} \qquad (A1)$$

The benefit for a PV in choosing non-cooperation strategy is-

$$\pi_{pd} = \frac{xB_p}{2} \tag{A2}$$

The average benefits for a PV in choosing mixed strategies can be derived as

$$\Pi_{pm} = y * \Pi_{pc} + (1-y) * \pi_{pd} \;= y\left(x\frac{B_p}{2} + \frac{B_p}{2} - C_p\right) + (1-y) * x\frac{B_p}{2}$$

$$= xy\frac{B_p}{2} + y\frac{B_p}{2} - yC_p + \frac{xB_p}{2} - \frac{xyB_p}{2}$$

$$= \frac{B_p}{2}(x+y) - yC_p \tag{A3}$$

Similarly,

The benefits for coal in choosing cooperation strategy are

$$\Pi_{cc} = y(B_c - C_c) + (1-y)\left(\frac{B_c}{2} - C_c\right) = yB_c - yC_c + \frac{B_c}{2} - C_c - \frac{yB_c}{2} + yC_c$$

$$= \frac{yB_c}{2} + \frac{B_c}{2} - C_c \tag{A4}$$

The benefits for coal in choosing non-cooperation strategy are

$$\pi_{cD} = \frac{yB_c}{2} \tag{A5}$$

The average benefits for a coal in choosing mixed strategies can be derived as

$$\Pi_{cm} = x * \Pi_{cc} + (1-x) * \pi_{cD} = x\left(\frac{yB_c}{2} + \frac{B_c}{2} - C_2\right) + (1-x) * \left(\frac{yB_c}{2}\right)$$

$$= \frac{xyB_c}{2} + \frac{xB_c}{2} - xC_c + \frac{yB_c}{2} - \frac{xyB_c}{2} = \frac{B_c}{2} * (x+y) - xC_c \tag{A6}$$

Based on these, if PV and coal both choose cooperation strategy, the replicator dynamics differential equation (variant with time) is

$$\frac{dy}{dt} = y\left(\Pi_{pc} - \Pi_{pm}\right) = y(x\frac{B_p}{2} + \frac{B_p}{2} - C_p - (\frac{B_p}{2}(x+y) - yC_p))$$

$$= y\left(\frac{xB_p}{2} + \frac{B_p}{2} - C_p - \frac{xB_p}{2} - \frac{yB_p}{2} + yC_p\right) = y\left(\frac{B_p}{2} - C_p - \frac{yB_p}{2} + yC_p\right)$$

$$= y\left\{\frac{B_p}{2}(1-y) - C_p(1-y)\right\}$$

$$= y(1-y)\left(\frac{B_p}{2} - C_p\right) \tag{A7}$$

$$\frac{dx}{dt} = x(\Pi_{cc} - \Pi_{cm}) = x\left(y\frac{B_c}{2} + \frac{B_c}{2} - C_c - \left(\frac{B_c}{2} * (x+y) - xC_c\right)\right)$$

$$= x\left(\frac{yB_c}{2} + \frac{B_c}{2} - C_c - \frac{B_c}{2}x - \frac{B_c}{2}y + xC_c\right) = x\left(\frac{B_c}{2}(1-x) - C_c(1-x)\right)$$

$$= x(1-x)\left(\frac{B_c}{2} - C_c\right) \qquad (A8)$$

The Jacobian matrix is as

$$J = \begin{bmatrix} (1-2y)\left(\frac{B_p}{2} - C_p\right) & 0 \\ 0 & (1-2x)\left(\frac{B_c}{2} - C_c\right) \end{bmatrix}$$
$(A9)$

Eigenvalue consider:

$$det(J) = \begin{bmatrix} (1-2y)\left(\frac{B_p}{2} - C_p\right) - \lambda & 0 \\ 0 & (1-2x)\left(\frac{B_c}{2} - C_c\right) - \lambda \end{bmatrix}$$

According to Eigenvalue condition,

$det(J) = 0$

$$\Rightarrow \begin{bmatrix} (1-2y)\left(\frac{B_p}{2} - C_p\right) - \lambda & 0 \\ 0 & (1-2x)\left(\frac{B_c}{2} - C_c\right) - \lambda \end{bmatrix} = 0$$

$$\Rightarrow \left\{(1-2y)\left(\frac{B_p}{2} - C_p\right) - \lambda\right\}\left\{(1-2x)\left(\frac{B_c}{2} - C_c\right) - \lambda\right\} = 0$$

Let, $a = (1-2y), b = \left(\frac{B_p}{2} - C_p\right),\ c = (1-2x),\ d = \left(\frac{B_c}{2} - C_c\right)$

$$\Rightarrow (ab - \lambda)(cd - \lambda) = 0$$

$$\Rightarrow abcd - ab\,\lambda - cd\,\lambda - \lambda^2 = 0$$

$$\Rightarrow \lambda^2 - \lambda(ab + cd) + abcd = 0$$

$$\Rightarrow \lambda^2 - \lambda\left\{(1-2y)\left(\frac{B_p}{2} - C_p\right) + \left((1-2x)\left(\frac{B_c}{2} - C_c\right)\right\} + (1-2y)\left(\frac{B_p}{2} - C_p\right)(1-2x)\left(\frac{B_c}{2} - C_c\right) = 0$$

$$\Rightarrow \lambda^2 - \lambda\left\{\left(\frac{B_p}{2} - C_p - 2y\frac{B_p}{2} + 2yC_p\right) + \left(\frac{B_c}{2} - C_c - 2x\frac{B_c}{2} + 2xC_c\right)\right\} + (1-2y)(1-2x)\left(\frac{B_p}{2} - C_p\right)\left(\frac{B_c}{2} - C_c\right) = 0$$

$$\Rightarrow \lambda^2 - \lambda\left(\frac{B_p}{2} - C_p - 2y\frac{B_p}{2} + 2yC_p + \frac{B_c}{2} - C_c - 2x\frac{B_c}{2} + 2xC_c\right) + (1 - 2x - 2y + 4xy)\left(\frac{B_pB_c}{4} - \frac{B_p}{2} * C_c -\right.$$

$C_p * \frac{B_c}{2} + C_p C_c) = 0$

$\Rightarrow \lambda_1(\lambda_2)$

$$= \frac{(\frac{B_p}{2} - C_p - \mathbf{2y}\frac{B_p}{2} + 2yC_p + \frac{B_c}{2} - C_c - 2x\frac{B_c}{2} + 2xC_c) \pm \sqrt{(\frac{B_p}{2} - C_p - 2y\frac{B}{2} + 2yC_p + \frac{B_c}{2} - C_c - 2x\frac{B}{2} + 2xC_c)^2 - 4.1.(1-2x-2y+4xy)\left(\frac{B_p}{2}\frac{B_c}{2} - \frac{B_p}{2} * C_c - C_p * \frac{B_c}{2} + C_p C_c\right)}}{2}$$

A10

**Game 2**

Payoff matrix of game 2

$$\begin{matrix} & \boldsymbol{CF\ (C)} & \boldsymbol{CF\ (D)} \\ \boldsymbol{PV\ (C)} & \frac{B_p}{2}+\frac{S}{2}, \frac{B_c}{2}+\frac{S}{2} & 0, B_c + S \\ \boldsymbol{PV\ (D)} & B_p + S, 0 & \frac{B_p}{2} - C_p, \frac{B_c}{2} - C_c \end{matrix}$$

We could get the expected benefit for PV chosen cooperation strategy is:

$$\Pi_{pc} = x\left(\frac{B_p}{2} + \frac{S}{2}\right) = x\frac{B_p}{2} + x\frac{S}{2} \qquad (A11)$$

The expected benefit for a PV in choosing non-cooperation strategy is:

$$\Pi_{pD} = x(B_p + S) + (1-x)\left(\frac{B_p}{2} - C_p\right)$$
$$= xB_p + xS + \frac{B_p}{2} - C_p - \frac{xB_p}{2} + xC_p = \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p \qquad (A12)$$

So, the average expected benefits for a PV in choosing mixed strategies can be derived as

$$\Pi_{pm} = y * \Pi_{pc} + (1-y) * \Pi_{pd}$$
$$= y\left(x\frac{B_p}{2} + x\frac{S}{2}\right) + (1-y) * \left(\frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p\right)$$
$$= xy\frac{E_p}{2} + xy\frac{S}{2} + \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p - \frac{yxE_p}{2} - yxS - \frac{yE_p}{2} + y\,C_p - xyC_p$$
$$= -xy\frac{S}{2} + \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p - \frac{yB_p}{2} + y\,C_p - xyC_p \qquad (A13)$$

Similarly,
The expected benefit for coal chosen cooperation strategy is:

$$\Pi_{CC} = y\left(\frac{B_c}{2} + \frac{S}{2}\right) = \frac{yB_c}{2} + \frac{yS}{2} \qquad (A14)$$

The expected benefit for coal chosen non-cooperation strategy is:

$$\pi_{CD} = y\,(B_c + S) + (1-y)\left(\frac{B_c}{2} - C_c\right) = yB_c + yS + \frac{B_c}{2} - C_c - y\frac{B_c}{2} + y\,C_c$$
$$= y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c \qquad (A15)$$

Then, the average expected benefits for a coal chosen mixed strategies can be derived as

$$\Pi_{cm} = x \times \Pi_{CC} + (1-x) \times \pi_{CD}$$
$$= x\left(\frac{yB_c}{2} + \frac{yS}{2}\right) + (1-x) * \left(y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c\right)$$
$$= x\frac{yB_c}{2} + x\frac{yS}{2} + y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c - xy\frac{B_c}{2} - x\,yS - \frac{xB_c}{2} + xC_c - xy\,C_c$$
$$= -x\frac{yS}{2} + y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c - \frac{xB_c}{2} + xC_c - xy\,C_c \qquad (A16)$$

Based on these, if PV and coal both choose cooperation strategy, the replicator dynamics differential equation (variant with time) is

$$\frac{dy}{dt} = y\left(\Pi_{pc} - \Pi_{pm}\right)$$
$$= y\left(x\frac{B_p}{2} + x\frac{S}{2} - \left(-xy\frac{S}{2} + \frac{xB_p}{2} + xS + \frac{B_p}{2} - C_p + xC_p - \frac{yB_p}{2} + y\,C_p - xyC_p\right)\right)$$
$$= y\left(x\frac{B_p}{2} + x\frac{S}{2} + xy\frac{S}{2} - \frac{xB_p}{2} - xS - \frac{B_p}{2} + C_p - xC_p + \frac{yB_p}{2} - y\,C_p + xyC_p\right)$$
$$= y\left(-x\frac{S}{2} + xy\frac{S}{2} - \frac{B_p}{2} + C_p - xC_p + \frac{yB_p}{2} - y\,C_p + xyC_p\right)$$
$$= y\left(x\frac{S}{2}(y-1) + \frac{B_p}{2}(y-1) - C_p(y-1) + xC_p(y-1)\right)$$
$$= y(y-1)\left(x\left(\frac{S}{2} + C_p\right) + \frac{B_p}{2} - C_p\right) \qquad (A17)$$

Again,

$$\frac{dx}{dt} = x(\Pi_{CC} - \Pi_{Cm})$$
$$= x\left(\frac{yB_c}{2} + \frac{yS}{2} - \left(-x\frac{yS}{2} + y\frac{B_c}{2} + yS + \frac{B_c}{2} - C_c + y\,C_c - \frac{xB_c}{2} + xC_c - xy\,C_c\right)\right)$$
$$= x\left(\frac{yB_c}{2} + \frac{yS}{2} + x\frac{yS}{2} - y\frac{B_c}{2} - yS - \frac{B_c}{2} + C_c - y\,C_c + \frac{xB_c}{2} - xC_c + xy\,C_c\right)$$
$$= x\left(\frac{yS}{2} + x\frac{yS}{2} - yS - \frac{B_c}{2} + C_c - y\,C_c + \frac{xB_c}{2} - xC_c + xy\,C_c\right)$$
$$= x\left(\frac{yS}{2} + x\frac{yS}{2} - yS - \frac{B_c}{2} + C_c - y\,C_c + \frac{xB_c}{2} - xC_c + xy\,C_c\right)$$

$$= x(\frac{yS}{2}(x-1) + \frac{B_c}{2}(x-1) - C_c(x-1) + y\, C_c(x-1))$$

$$= x(x-1)(\frac{yS}{2} + \frac{B_c}{2} - C_c + y\, C_c)$$

$$= x(x-1)\left(y\left(\frac{S}{2} + C_c\right) + \frac{B_c}{2} - C_c\right) \qquad (A18)$$

The Jacobian matrix is as

$$J = \begin{bmatrix} (2y-1)(x\left(\frac{S}{2} + C_p\right) + \frac{B_p}{2} - C_p) & y(y-1)(\frac{S}{2} + C_p) \\ x(x-1)(\frac{S}{2} + C_c) & (2x-1)(y\left(\frac{S}{2} + C_c\right) + \frac{B_c}{2} - C_c) \end{bmatrix}$$

$$(A19)$$

Eigen value consider as:

$$det(J) = \begin{bmatrix} (2y-1)(x\left(\frac{S}{2} + C_p\right) + \frac{B_p}{2} - C_p) - \lambda & y(y-1)(\frac{S}{2} + C_p) \\ x(x-1)(\frac{S}{2} + C_c) & (2x-1)(y\left(\frac{S}{2} + C_c\right) + \frac{B_c}{2} - C_c) - \lambda \end{bmatrix}$$

According to Eigen value condition,

$$det(J) = 0$$

$$\Rightarrow \begin{bmatrix} (2y-1)(x\left(\frac{S}{2} + C_p\right) + \frac{B_p}{2} - C_p) - \lambda & y(y-1)(\frac{S}{2} + C_p) \\ x(x-1)(\frac{S}{2} + C_c) & (2x-1)(y\left(\frac{S}{2} + C_c\right) + \frac{B_c}{2} - C_c) - \lambda \end{bmatrix} = 0$$

$$\Rightarrow \left( (2y-1)(x\left(\frac{S}{2} + C_p\right) + \frac{B_p}{2} - C_p) - \lambda\right)\left( (2x-1)(y\left(\frac{S}{2} + C_c\right) + \frac{B_c}{2} - C_c) - \lambda\right) - \left( x(x-1)(\frac{S}{2} + C_c)\right)\left( y(y-1)(\frac{S}{2} + C_p)\right) = 0$$

$$\begin{aligned}\lambda_1 &= \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p + 2B_c x - 4C_c x - 2C_p x - Sx + 2B_p y - 2C_c y - 4C_p y - Sy + 4C_c xy + 4C_p xy \\ &+ 4Sxy \\ &- \sqrt{\left(B_c + B_p - 2C_c - 2C_p - 2B_c x + 4C_c x + 2C_p x + Sx - 2B_p y + 2C_c y + 4C_p y + Sy - 4C_c xy - 4C_p xy - 4Sxy\right)^2} \\ &- 4\big(4C_c C_p - 12C_c C_p x - 2C_c Sx + 8C_c C_p x^2 + 4C_c Sx^2 - 12C_c C_p y - 2C_p Sy + 32C_c C_p xy + 4C_c Sxy + 4C_p Sxy \\ &- 20C_c C_p x^2 y - 10C_c Sx^2 y - 2C_p Sx^2 y - S^2x^2y + 8C_c C_p y^2 + 4C_p Sy^2 - 20C_c C_p xy^2 - 2C_c Sxy^2 - 10C_p Sxy^2 \\ &- S^2xy^2 + 12C_c C_p x^2y^2 + 6C_c Sx^2y^2 + 6C_p Sx^2y^2 + 3S^2x^2y^2 \\ &+ B_c(-1+2x)\big(B_p + 2C_p(-1+x) + Sx\big)(-1+2y) + B_p(-1+2x)(-1+2y)(2C_c(-1+y) + Sy)\big)\big)\end{aligned}$$

$$(A20)$$

$$\lambda_2 = \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p + 2B_c x - 4C_c x - 2C_p x - Sx + 2B_p y - 2C_c y - 4C_p y - Sy + 4C_c xy + 4C_p xy + 4Sxy + \sqrt{\left(B_c + B_p - 2C_c - 2C_p - 2B_c x + 4C_c x + 2C_p x + Sx - 2B_p y + 2C_c y + 4C_p y + Sy - 4C_c xy - 4C_p xy - 4Sxy\right)^2 - 4\left(4C_cC_p - 12C_cC_p x - 2C_c Sx + 8C_cC_p x^2 + 4C_c Sx^2 - 12C_cC_p y - 2C_p Sy + 32C_cC_p xy + 4C_c Sxy + 4C_p Sxy - 20C_cC_p x^2 y - 10C_c Sx^2 y - 2C_p Sx^2 y - S^2x^2y + 8C_cC_p y^2 + 4C_p Sy^2 - 20C_cC_p xy^2 - 2C_c Sxy^2 - 10C_p Sxy^2 - S^2xy^2 + 12C_cC_p x^2y^2 + 6C_c Sx^2y^2 + 6C_p Sx^2y^2 + 3S^2x^2y^2 + B_c(-1+2x)\left(B_p + 2C_p(-1+x) + Sx\right)(-1+2y) + B_p(-1+2x)(-1+2y)(2C_c(-1+y) + Sy)\right)}) \quad (A21)$$

$x = 0, y = 0$

$$\lambda_1 = \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p - \sqrt{((B_c + B_p - 2C_c - 2C_p)^2 - 4(-2B_pC_c + B_c(B_p - 2C_p) + 4C_cC_p))}) \quad (A22)$$

$$\lambda_2 = \frac{1}{4}(-B_c - B_p + 2C_c + 2C_p + \sqrt{((B_c + B_p - 2C_c - 2C_p)^2 - 4(-2B_pC_c + B_c(B_p - 2C_p) + 4C_cC_p))}) \quad (A23)$$

$x = 0, y = 1$

$$\lambda_1 = \frac{1}{4}\left(-B_c + B_p - 2C_p - S - \sqrt{\left(B_c - B_p + 2C_p + S\right)^2 - 4(-B_c(B_p - 2C_p) - B_pS + 2C_pS))}\right) \quad (A24)$$

$$\lambda_2 = \frac{1}{4}\left(-B_c + B_p - 2C_p - S + \sqrt{\left(B_c - B_p + 2C_p + S\right)^2 - 4(-B_c(B_p - 2C_p) - B_pS + 2C_pS))}\right) \quad (A25)$$

$x = 1, y = 0$

$$\lambda_1 = \frac{1}{4}\left(B_c - B_p - 2C_c - S - \sqrt{\left((-B_c + B_p + 2C_c + S\right)^2 - 4(2B_pC_c + 2C_cS - B_c\left(B_p + S\right)))}\right) \quad (A26)$$

$$\lambda_2 = \frac{1}{4}\left(B_c - B_p - 2C_c - S + \sqrt{\left((-B_c + B_p + 2C_c + S\right)^2 - 4(2B_pC_c + 2C_cS - B_c\left(B_p + S\right)))}\right) \quad (A27)$$

$x = 1, y = 1$

$$\lambda_1 = \frac{1}{4}\left(B_c + B_p + 2S - \sqrt{(-B_c - B_p - 2s)^2 + 4(B_pS + S^2 + Bc(B_p + S))}\right) \quad (A28)$$

$$\lambda_2 = \frac{1}{4}\left(B_c + B_p + 2S + \sqrt{(-B_c - B_p - 2s)^2 + 4(B_pS + S^2 + Bc(B_p + S))}\right) \quad (A29)$$

$$x = \frac{C_p - \frac{B_p}{2}}{C_p + \frac{S}{2}}, \qquad y = \frac{C_c - \frac{B_c}{2}}{C_c + \frac{S}{2}}$$

$$\lambda_1 = -\frac{1}{2}\sqrt{\frac{(B_c - 2C_c)(B_p - 2C_p)(B_c + S)(B_p + S)}{(2C_c + S)(2C_p + S)}} \quad (A30)$$

$$\lambda_2 = \frac{1}{2}\sqrt{\frac{(B_c - 2C_c)(B_p - 2C_p)(B_c + S)(B_p + S)}{(2C_c + S)(2C_p + S)}} \quad (A31)$$