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# Hydropower licensing and climate change: Insights from cooperative game theory

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ABSTRACT

Cooperative game theory solutions can provide useful insights into how parties may use water and environmental resources and share any benefits of cooperation. Here, a method based on Nash and Nash–Harsanyi bargaining solutions is developed to explore the Federal Energy Regulatory Commission (FERC) relicensing process, in which owners of non-federal hydropower projects in the United States have to negotiate their allowable operations, with other interest groups (mainly environmental). Linkage of games to expand the feasible solution range and the “strategic loss” concept are discussed and a FERC relicensing bargaining model is developed for studying the bargaining stage (third stage) of the relicensing process. Based on the suggested solution method, how the lack of incentive for cooperation results in long delay in FERC relicensing in practice is explained. Further, potential effects of climate change on the FERC relicensing are presented and how climate change may provide an incentive for cooperation among the parties to hasten the relicensing is discussed. An “adaptive FERC license” framework is proposed, based on cooperative game theory, to improve the performance and adaptability of the system to future changes with no cost to the FERC, in face of uncertainty about future hydrological and ecological conditions.

## 1. Introduction

Non-federal hydroelectric projects in the United States are under the regulatory authority of Federal Energy Regulatory Commission (FERC), which since 1935 has issued thousands of operation licenses [1]. FERC licenses are usually valid for 30–50 years. To legally continue operating, the project owner must file for a new license at the end of the initial license period. A license is a regulatory document that permits the project owner to use public waters for hydropower generation and specifies conditions for construction, operation, and maintenance of the project [2].

FERC's official statutory objective is the development of hydropower production. However, this objective should be balanced against environmental and other basin interests and implications of hydropower generation [1]. Thus, FERC is required to involve basin stakeholders and interest groups, which has strengthened the role of other interests in balancing the power benefits against the environmental effects of hydroelectric generation. Hydropower generation creates significant bioregional effects on the health of aquatic and riparian ecosystems and the periodic relicensing of hydropower facilities regulated by FERC is the only formal opportunity to reduce these impacts through new license conditions and settlement agreements that better reflect the range of modern societal goals [1].

Table 1 presents a brief summary of the FERC relicensing process. At least 5 years, but not more than five-and-half years, before the expiration of the current license, the licensee files a Notice of Intent for application for a new license (stage 1). At least a year before the expiration of the current license, the licensee files a relicense application. After reviewing the application and seeking additional information or studies, FERC formalizes the application with a notice of Federal Register (stage 2). During the next stage (stage 3) a wide range of interest groups submit comments, protests, and requests for information or further studies from the licensee or FERC. This stage is the only opportunity for concerned individuals and interest groups to affect operation of the dam through the formal regulatory process. In the final step (stage 4) FERC holds a hearing regarding the relicense application and makes its final decision. FERC decisions at this stage are important to all the stakeholders. Instead of relicensing the project, FERC can recommend a federal takeover of the project with compensation to the current licensee or even issue a non-power license for conversion of the project to a non-hydropower use. Nevertheless, FERC has never exercised this option.

The official relicensing process is expected to take 5 years to complete. However, only 27% of licenses issued by FERC between 1982 and 1988 took the expected 5 years, with the longest requiring 21 years to complete [1]. In recent years applications tend to languish longer. Most variability in processing time is associated with stage 3 of the relicensing process. The final decision is up to the FERC, but agreements among stakeholders during stage 3 can

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**Table 1**
Different stages of the FERC relicensing process.

| Stage | Involved parties | Description |
|---|---|---|
| 1 | Licensee | The licensee files a Notice of Intent to apply for a new license (*5–5.5 years before expiration of the current license*) |
| 2 | FERC | FERC formalizes the relicense application with a notice of Federal Register (*1 year before expiration of the current license*) |
| 3 | Licensee & Interest groups | Interests groups submit comments, protests, and requests for information or further studies from the licensee or FERC. This stage is the only opportunity for concerned individuals and groups to affect operations of the dam through the formal regulatory process. Interested parties can present alternative/compromise plans through bargaining (*expected to be completed by 5 years*) |
| 4 | FERC, Licensee, & Interest groups | FERC holds a hearing regarding the relicense application and makes its final decision |

accelerate the process significantly [1]. As long as the new license is not issued and FERC does not make its decision, operations are based on the existing license.

With many projects facing relicensing in the United States by 2020, FERC relicensing will be complicated, lengthy and resource-intensive. This problem can be exacerbated by expected climate changes, which will have significant implications for various environmental resources and ecosystems, as well as hydropower production. Although changes in operations may help adaptation to new climatic conditions and minimize revenue losses to some extent, environmental constraints, imposed on operations by FERC as a result of pressure by interest groups, might limit the operators flexibility to adapt for power generation.

It is important to environmental advocates that long-term licenses and agreements can address changes and reduce the likelihood that operations will produce irreversible ecosystem impacts before subsequent license renewals. Thus, they make as much effort as possible in stage 3. Generally, environmental interest groups are expected to seek to hasten the process (independent of final relicensing outcome) to save endangered riverine resources while dam owners and hydropower investors are mostly seeking to slow down process to postpone financially constraining environmental mitigation requirements. However, as discussed later, climate change may reverse this trend as environmental and revenue losses may provide an incentive for cooperation to speed license renewal in coming decades.

Game theory, the mathematical study of cooperation and competition, can be used to interpret the behavior of decision makers and to suggest solutions which increase their gain under win–win resolutions [3]. Cooperative game theory has been previously used in studying water and environmental resources conflicts (see reviews by Madani [3], Zara et al. [4], and Parrachino et al. [5]). Cooperative game theory solutions or stability definitions can provide useful insights into how stakeholders with different interests plan their use of water and environmental resources and suggest how parties can share gains from cooperation in an efficient and fair manner.

The main objective of this paper is to apply cooperative game theory as a method for understanding causes of delay in stage 3 of FERC relicensing in general and exploring why the current structure of the FERC license (with fixed terms as opposed to an adaptive license, explained later) might deteriorate the performance of the hydropower system and its environment under climate change. This study suggests a cooperative game theoretic method based on the well-known Nash [6] and Nash–Harsanyi [7,8] bargaining solutions for gaining insights and finding the conditions under which parties to a FERC license are willing to cooperate for a new license. The "strategic loss" concept is discussed and a revision to the Nash and Nash–Harsanyi cooperative stability definitions is suggested to make them applicable to a linked game upon which a FERC relicensing bargaining model is developed. The method suggested here can provide insights into stage 3 of FERC relicensing – the most complicated stage. The FERC relicensing bargaining model can support ongoing bargaining and negotiations between the interested parties and may be used to investigate whether climate change can be an incentive for cooperation and a speedier relicensing process. Further, the paper suggests a bargaining framework to be added to FERC licenses to provide more flexibility and adaptability to climate change.

## 2. Revising the Nash bargaining solution for connected games

While often parties to water and environmental conflicts can gain from cooperation, they fail to cooperate in many occasions as finding a fair allocation scheme which enforces cooperation efficiently is challenging. Nash [6] suggested the following non-linear optimization model (Eqs. (1)–(4)) to determine an optimal solution to the 2-player bargaining game over sharing a resource under cooperation (or sharing the gains from cooperation), and to enforce a fair and efficient allocation of the resource (gains from cooperation) among the rational bargainers (cooperative parties) who have perfect information about the conditions of the problem:

$$\Omega = \max(x_1 - d_1)(x_2 - d_2) \tag{1}$$

subject to:

$$\sum_{i=1}^{2} x_i \leqslant S \tag{2}$$

$$x_i \geqslant d_i \text{ (rationality condition)} \tag{3}$$

$$x_i, d_i \geqslant 0 \tag{4}$$

where for player $i = 1, 2$:

$S$ = total available resource; $x_i$ = share of player $i$ from the resource under cooperation; $d_i$ = share of player $i$ from the resource when acting individually (non-cooperation) (setting $d_i = 0$, $x_i$ will be the gain of player $i$ from cooperation); and $\Omega$ is the unique Pareto-optimal solution of the Nash bargaining game. The Pareto-optimal solution is the solution in which none of the parties can increase his gain without decreasing the gain of at least one other party.

Harsanyi [7,8] generalized the Nash cooperative solution for a 2-player bargaining game to an $n$-players game:

$$\Omega = \max \prod_{i=1}^{n} (x_i - d_i) \tag{5}$$

subject to:

$$\sum_{i=1}^{n} x_i \leqslant S \tag{6}$$

$$x_i \geqslant d_i \tag{7}$$

$$x_i, d_i \geqslant 0 \tag{8}$$

Just and Netanyahu [9] showed how the feasible solution set (the set of all possible solutions to the problem) can be expanded through connecting isolated (independent or irrelevant) games. Since bargaining over one issue might not always result in a cooperative resolution (when $\Omega = 0$) it might benefit negotiators to bargain over several issues at the same time. The feasible set is expanded in this case because outcomes that are not desired by all parties in isolated games due to individual rationality constraints may become desired when compensated by offsetting gains from connected issues. Interconnection is only beneficial when each party is stronger than the other at least in one of the sub-games. In such cases, one party is willing to lose in one game to gain in another. A Nash solution for a 2-player bargaining game can be written for $k$ linked 2-player games as:

$$\Omega = \max\left(\sum_{j=1}^{k} x_{1,j} - d_{1,j}\right)\left(\sum_{j=1}^{k} x_{2,j} - d_{2,j}\right) \tag{9}$$

subject to:

$$\sum_{i=1}^{2} x_{i,j} \leqslant S_j \tag{10}$$

$$\sum_{j=1}^{k} x_{i,j} \geqslant \sum_{j=1}^{k} d_{i,j} \tag{11}$$

$$x_{i,j}, d_{i,j} \geqslant 0 \tag{12}$$

where for player $i = 1, 2$:

$x_{i,j}$ = share of player $i$ in the $j$th sub-game ($j = 1,2,\ldots,k$) when parties cooperate in the linked game; $d_{i,j}$ = share of player $i$ when acting individually (non-cooperation) in the $j$th sub-game; and $S_j$ = total available resource in sub-game $j$. Setting $d_{i,j} = 0\left(\sum_{j=1}^{k} d_{i,j} = 0\right)$, $\sum_{j=1}^{k} x_{i,j}$ will be the gain of player $i$ from cooperation.

Similarly, the Nash–Harsanyi solution for $k$ linked $n$-player games becomes:

$$\Omega = \max \prod_{i=1}^{n}\left(\sum_{j=1}^{k} x_{i,j} - d_{i,j}\right) \tag{13}$$

subject to:

$$\sum_{i=1}^{n} x_{i,j} \leqslant S_j \tag{14}$$

$$\sum_{j=1}^{k} x_{i,j} \geqslant \sum_{j=1}^{k} d_{i,j} \tag{15}$$

$$x_{i,j}, d_{i,j} \geqslant 0 \tag{16}$$

for player $i = 1,2,\ldots,n$.

If $\Omega > 0$ and there exists a $j$ for which $x_{i,j} < d_{i,j}$ player $i$ is a "strategic loser" in game $j$. This player is willing to lose in game $j$ when he knows his loss in game $j$ keeps him in the coalition and his gain from cooperation in the larger game (composed of $k$ interconnected games) exceeds his overall gain from $k$ isolated games. Player $i$ gains less when he plays each game independently and is not willing to lose in any game to gain in others. Strategic loss may exist to players of the larger (interconnected) game when each player is stronger than the others at least in one of the sub-games. Willingness for "strategic loss in cooperation" expands the feasible solution set to the bargaining game where if $k$ separated games are played by player $i$, there will be no strategic loss, and the final solution will be inferior to a solution to the linked game.

## 3. FERC relicensing bargaining game

During stage 3 of relicensing, environmental groups and hydropower project owners are expected, respectively, to hasten and slow the process. However, empirical results show that in practice both groups of interveners are significantly effective at slowing the process [1]. With help from the Nash solution for this game it is possible to find why the parties might lack incentive to cooperate, resulting in delay in stage 3.

The third stage of FERC relicensing can be modeled as a bargaining game where two players – the hydropower generator and a coalition of environmental interest groups at a given site – bargain to increase their benefit from the available water. Here, for simplicity it is assumed that the parties bargain over water quantity. In practice, parties may be concerned about flow regime (water quantity, ramping rates, occasional pulse flows, etc.) and temperature. $d_{env,j}$ and $d_{hp,j}$ are, respectively, the gains of environmentalists and the hydropower generator in time $j$ from their shares based on the current license (the parties have regulated shares at any period $j$ based on the current operations and environmental constraints imposed by the existing license). In this game, a hydropower generator wants to operate the dam to maximize its revenue, while interest groups want the dam to be operated to maximize their utility (sportfishing, boating, historical, endangered species, water quality, and recreation).

In the third stage of FERC relicensing, the two players do not bargain over their shares in a given time step in isolation from other time periods as they are aware of the fact that without interconnection of the $k$ independent games, it is impossible to find any superior solution. In other words, in a given time, isolated from other time steps, loss to one party is the gain to the other party, $\Omega$ equals zero, the strategic loss option is not available, and no win–win solution is possible. Thus, the parties always consider a larger (e.g. annual) game and do not bargain over their share only in time $j$ (e.g. hour, day, week, month, or season) without considering their shares in other periods. The Nash bargaining solution for the third stage of the FERC relicensing game can be written as:

$$\Omega = \max\left(\sum_{j=1}^{k} U_j(x_{env,j}) - U_j(d_{env,j})\right)\left(\sum_{j=1}^{k} R_j(x_{hyd,j}) - R_j(d_{hyd,j})\right) \tag{17}$$

subject to individual rationality and resources availability constraints, where for player $i$ = *Environmentalists, Hydropower Operator* and time step $j = 1,2,\ldots,k$:

$U(x_{env,j})$ = utility of the environmentalists in cooperative case at time $j$ from their share $x_{env,j}$; $U(d_{env,j})$ = utility of the environmentalists in non-cooperative case at time $j$ from their regulated share $d_{env,j}$; $R(x_{hyd,j})$ = revenue of the hydropower generator in cooperative case at time $j$ from its share $x_{hyd,j}$; $R(d_{hyd,j})$ = revenue of the hydropower generator in non-cooperative case at time $j$ from its regulated share $d_{hyd,j}$.

For a dam like the one in Fig. 1 with turbines below the dam and no diversion tunnel, $x_{env,j} = x_{hyd,j}$ and $d_{env,j} = d_{hyd,j}$, because the amount of water through the turbine flows in the stream.

Modeling stage 3 of the FERC relicensing game using cooperative game theory enables us to find if cooperation between the parties is possible and if so, what flow values bring collaboration between the conflicting parties. If $\Omega > 0$ then there exists a $j$ for which one of the payers is a strategic loser ($U(x_{env,j}) < U(d_{env,j})$ or $R(x_{hp,j}) < R(d_{hp,j})$) and is willing to lose in period $j$ to increase its gain in the overall interconnected game. However, If $\Omega = 0$ is the only solution to Eq. (17), the parties are not willing to cooperate because they cannot come up with any compromise solution. In bargaining games like this, a player does not cooperate and the conflict has no cooperative resolution if he does not receive at least as much as he can get in the non-cooperative game. This can cause a long a delay in FERC relicensing. In such cases, cooperation is not the parties' dominant strategy as it is not beneficial to the players. Thus, when unsuccessful in bargaining based on Eq. (17), the hydroelectricity generator tries to delay the process to preserve its current generation pattern and capacity and avoid costly environmental mitigation requirements (as long as the new license is not issued operations are based on the current license). On the other hand, the environmental interest groups who are unsuccessful in making the generators cooperate, seek to delay the process to ensure their interests are finally implemented through methods

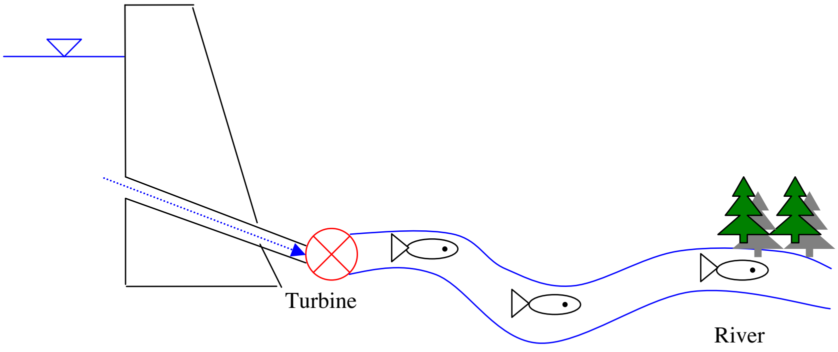

**Fig. 1.** Hydropower generation site without a diversion unit.

other than bargaining such as asking for assistance from Congress or FERC through formal regulatory and legal processes.

When $\Omega = 0$, delaying is the dominant strategy, and when $\Omega > 0$, parties tend to cooperate. One benefit of using cooperative game theory to study FERC relicensing is the ability of finding conditions (e.g. flow values in this example) for each time step, which makes cooperation possible when parties prefer to cooperate. Agreement on enforcing such numbers by the terms and conditions of the FERC license can make cooperation possible when both parties can gain more (win–win situation). To show how Eq. (17) can be used to find if cooperation or delaying is the dominant strategy for players, a numerical example is presented.

## 4. FERC relicensing bargaining model

Suppose a group of environmentalists below Dam A on River B and the operator of this single-purpose high-elevation hydropower reservoir with no diversion unit (Fig. 1) and no carry-over storage, are in the FERC relicensing process. The environmentalist group is concerned with the effects of reservoir operations and changes in stream flows and temperatures on the population of Fish C in River B and are negotiating over the monthly instream flows with the project owners. Currently, the reservoir is operated based on the terms and conditions of the existing license, which has been in use for the past 25 years. These terms and conditions include the minimum and maximum monthly instream flows (Fig. 2) for maximizing the survival rate of Fish C. The capacity of the reservoir is 140 million cubic meters with the turbine generation capacity of 1528 MW h per month.

The benefit and utility to each party in each month should be specified for use in Eq. (17). Monthly revenue to the hydropower generator can be calculated, from hydropower prices and generation. Madani and Lund [10] developed a method for incorporating the effects of off-peak and on-peak pricing on hydropower generation. This method, which has been used in California's EBHOM (Energy-Based Hydropower Optimization Model), estimates the average monthly hydropower price based on the hours of turbine operation or proportion of monthly generation capacity used. This method is used here for incorporating the non-linear relationship of hydropower generation and pricing. Real-time hourly hydropower prices across California were used to estimate the hydropower prices based on the proportion of generation capacity used. Using this method, monthly hydropower revenue can be calculated as:

$$Z_j(G_j) = P_j(g_j) \times G_j \tag{18}$$

where:

$Z_j$ = hydropower revenue in month $j$; $G_j$ = hydropower generation in month $j$ (MW h/month); $g_j$ = the proportion of monthly generation capacity used $\left(g_j = \frac{G_j}{G_{cap}}\right)$; and $P_j(g_j)$ = price of electricity in month $j$ ($/MW h) when generation is equal to $g_j$.

The reservoir is operated for revenue maximization (hydropower operating costs are essentially fixed at monthly scale), based on the following hydropower optimization model (Eqs. (19)–(27)):

$$Max\ Z = \sum_{j=1}^{12} Z_j(G_j) \tag{19}$$

subject to:

$$S_1 = big \text{ (initial condition)} \tag{20}$$

$$S_{min} \leqslant S_j \leqslant S_{max}, \quad \forall j \tag{21}$$

$$S_{max} - S_{min} \leqslant Scap \text{ (storage capacity constraint)} \tag{22}$$

$$S_j = I_{j-1} + S_{j-1} - R_{j-1} \text{ (conservation of mass)}, \quad \forall j \tag{23}$$

$$G_i \leqslant R_j \times h \times \lambda, \quad \forall j \tag{24}$$

$$G_i \leqslant Gcap \text{ (generation capacity constraint)}, \quad \forall j \tag{25}$$

$$R_{min\,j} \leqslant R_j \leqslant R_{max\,j}, \quad \forall j \tag{26}$$

$$G_j, S_j, R_j \geqslant 0 \text{ (non-negativity)}, \quad \forall j \tag{27}$$

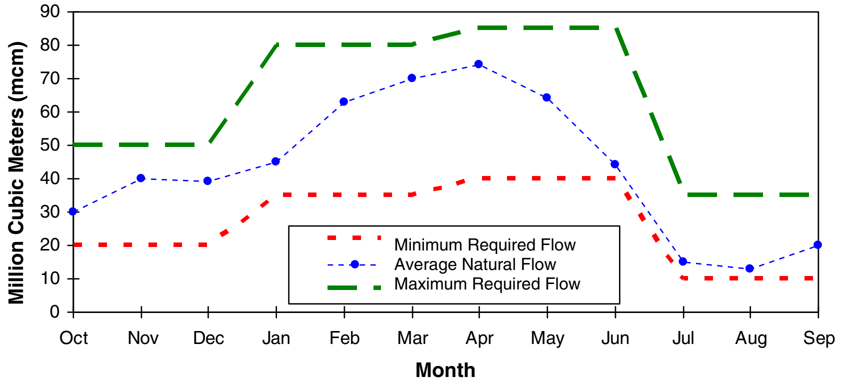

**Fig. 2.** Monthly unimpaired flow regime of River B and minimum and maximum flow requirements below Dam A.

where for $j = 1,2,3,\ldots,12$:

$Z$ = annual hydropower benefit; $S_j$ = water storage at the beginning of month $j$ ($m^3$) (a decision variable); $Scap$ = reservoir storage capacity ($m^3$); $big$ = an arbitrary large number greater than or equal to $Scap$; $S_{min}$ = minimum monthly water storage during the year (12 months period) ($m^3$) (a decision variable); $S_{max}$ = maximum monthly water storage during the year ($m^3$) (a decision variable); $I_j$ = inflow to reservoir (upstream runoff) in month $j$ ($m^3/s$); $R_j$ = water release from the reservoir in month $j$ ($m^3/s$) (a decision variable); $R_{min,j}$ = minimum release (instream flow) in month $j$, enforced by the FERC license ($m^3/s$); $R_{max,j}$= maximum release (instream flow) in month $j$, enforced by the FERC license ($m^3/s$); $Gcap$ = generation capacity (MW h/month); $h$ = turbine head (m); and $\lambda$ = turbine efficiency.

The head-storage effect is minimal in high-elevation reservoirs, so energy head is assumed constant across all months (Eq. (24)). Conventionally, in hydropower operation models storage at beginning of one month is set to zero (initial condition). However, by doing this optimal refill and drawdown cycles may not be found unless the model is run 12 times, each time by a different initial month. Eqs. (20)–(22), suggested by Madani and Lund [10], allows finding the optimal operations and drawdown and refill cycles with only one model run. It is assumed that Reservoir A has no carry-over storage. (This assumption is for simplicity only. The suggested method can be also applied to systems with carry-over storage.) Thus, operation decisions in each year are independent from other years. Minimum and maximum monthly stream flows below the reservoir are set by the existing FERC license and as long as a license has not been renewed, they do not change. The total annual hydropower revenue with average natural inflows based on the current license is \$ 578,746 (Eq. (19)).

Calculating utilities for the environmentalist group is more controversial. Here, it is assumed that the highest fish survival is with the unimpaired flow (Fig. 2). Any deviation from the natural flow regime reduces the fish population. Monthly fish population penalties are defined as:

$$FP_j(R_j) = w_j \times |R_j - R_{n,j}|^2 \tag{28}$$

where for ($j = 1,2,\ldots,12$):

$FP_j$ = fish penalty in month $j$; $R_{n,j}$ = historic average natural flow of the river; and $w_j$ = weight of penalty in month $j$.

It is assumed that the environmentalist group is trying to minimize total annual penalties, maximizing the population of Fish C through the downstream flow requirements. The parties have agreed on such requirements and during the past 25 years they have been enforced by the FERC license of project A. The deviation in instream flow below the dam increases the fish penalty exponentially. Fish penalties vary across the months for the same amount of flow deviation from the natural stream flow, as juvenile fish are more sensitive than adult fish to flow changes. Therefore, monthly weights (Table 2) are assigned to fish penalties where the weights decrease as fish age. The annual fish penalty ($FP$) for the current operations based on the existing license is the sum of the monthly fish penalties:

$$FP = \sum_{j=1}^{12} FP_j(R_j) \tag{29}$$

which is equal to 3.25.

Now, the parties are in the third stage of the FERC relicensing, negotiating over the monthly instream flows. Based on Eq. (17), it is possible to find if the two players are willing to cooperate and agree over new sets of monthly instream flows and changes in operations required to make cooperation possible. Considering Eqs. (17)–(29), the FERC relicensing bargaining model for project A is as follows:

**Table 2**
Monthly fish penalty weights.

| Month | Fish penalty weights |
|---|---|
| October | 0.35 |
| November | 0.35 |
| December | 0.35 |
| January | 1.00 |
| February | 1.00 |
| March | 1.00 |
| April | 0.80 |
| May | 0.80 |
| June | 0.80 |
| July | 0.50 |
| August | 0.50 |
| September | 0.50 |

$$\Omega = \max\left(\sum_{j=1}^{12} FP_j(R_j) - FP_{old}\right)\left(\sum_{j=1}^{12} Z_j(G_j) - Z_{old}\right) \tag{30}$$

subject to:

$$\sum_{j=1}^{12} FP_j(R_j) \leqslant FP_{old} \text{ (rationality condition)} \tag{31}$$

$$Z_{old} \leqslant \sum_{j=1}^{12} Z_j(G_j) \text{ (rationality condition)} \tag{32}$$

$$Z_j(G_j) = P_j(g_j) \times G_j \tag{18}$$

$$S_1 = big \text{ (initial condition)} \tag{20}$$

$$S_{min} \leqslant S_j \leqslant S_{max}, \quad \forall j \tag{21}$$

$$S_{max} - S_{min} \leqslant Scap \text{ (storage capacity constraint)} \tag{22}$$

$$S_j = I_{j-1} + S_{j-1} - R_{j-1} \text{ (conservation of mass)}, \quad \forall j \tag{23}$$

$$G_i \leqslant R_j \times h \times \lambda, \quad \forall j \tag{24}$$

$$G_i \leqslant Gcap \text{ (generation capacity constraint)}, \quad \forall j \tag{25}$$

$$G_j, S_j, R_j \geqslant 0 \text{ (non-negativity)}, \quad \forall j \tag{27}$$

$$FP_j(R_j) = w_j \times |R_j - R_{n,j}|^2 \tag{28}$$

$$FP = \sum_{j=1}^{12} FP_j(R_j) \tag{29}$$

where for $j = 1,2,3,\ldots,12$:

$FP_{old}$ = annual fish penalty for current optimal hydropower operations based on the current license (Eq. (29)); and $Z_{old}$ = maximum annual hydropower revenue based on the current license (Eq. (19)).

Eq. (26) (requirements of the old FERC license) were not put in the FERC relicensing bargaining model, as using them limits the feasible set and the results will not be anything other than zero. By not including them, the feasible bargaining set is expanded and the parties might find a solution preferred by both.

The only solution to the FERC relicensing bargaining model (a non-linear optimization model which can be solved using non-linear optimization solvers) for Dam A with the given annual river flow pattern, fish penalties, and hydropower prices is $\Omega = 0$. So, similar to most parties to the FERC relicensing processes in the United States, no immediate cooperative solution is available to the environmentalists and hydropower operator in this example and there may be a long delay in stage 3 of FERC relicensing.

The bargaining model developed here can provide insights into FERC relicensing projects. This model can support the third stage of FERC relicensing as a Negotiation Support System (NSS) to suggest cooperative solutions under different conditions. FERC bargaining games do not always have a non-cooperative solution ($\Omega = 0$). Changes in conditions of the problem (e.g. turbine generation capacity, reservoir storage capacity, natural flow regime, hydropower prices, and fish penalties) over time are likely. Such changes may result in cooperative solutions ($\Omega > 0$). For instance, if recent studies suggest that fish penalties differ from what would have estimated earlier due to biological change in the fish or updated information on state of ecosystem, the change in the fish penalty weights or functions might result in new solutions to the FERC relicensing problem. For project A, if fish penalties change to those given in Table 3, the FERC relicensing bargaining model has a solution $\Omega > 0$, preferred by both parties. In this case, the parties may decide to cooperate and agree on new sets of monthly instream flows (enforced through the FERC license), or wait to gain better solutions in the future through other methods (e.g. asking for assistance from Congress or FERC through formal regulatory and legal processes or filing lawsuits against the hydropower operator). Table 4 shows the gains of each party when new fish penalty weights are applied. Although hydropower operator benefit does not increase significantly with cooperation, the risk of future reduction in revenues decreases when the operator is willing to cooperate to finalize the third stage of the process to get a new license.

**Table 3**
New monthly fish penalty weights due to biological evolution of the fish.

| Month | Fish penalty weights |
|---|---|
| October | 0.40 |
| November | 0.40 |
| December | 0.40 |
| January | 0.90 |
| February | 0.90 |
| March | 0.90 |
| April | 0.80 |
| May | 0.80 |
| June | 0.80 |
| July | 0.70 |
| August | 0.70 |
| September | 0.70 |

**Table 4**
Gains of each party with the old and new fish penalty weights.

| Case description | Fish penalty | Hydropower revenue |
|---|---|---|
| Operations based on the existing license (original fish penalty weights) | 3.25 | $ 578,746 |
| Operations based on the existing license (new fish penalty weights) | 4.29 | $ 578,746 |
| Operations based on the new agreement (new fish penalty weights) | 4.21 | $ 578,880 |

Figs. 3–5 show monthly hydropower generation, hydropower revenues, and fish penalties under non-cooperative and cooperative cases when new fish penalty weights are applied. These figures show how linking the 12 monthly games is useful and how strategic loss can result in more gain in the larger game. Here, the hydropower generator reduces its generation in half the year for more generation in the other half. This makes the hydropower generator a strategic loser in half of the year and a winner in the other half, with higher overall gain. On the other hand, the environmentalists are strategic loser in 3 months and winner in 9 months, with overall annual fish penalty reduction of 2% under cooperation (Table 4).

Fig. 6 shows how the optimal trade-off curve (Pareto-optimal surface) and the optimal solution to the bargaining game can change with changes in the problem. If current operations are at point A, the bargaining game has a solution ($\Omega > 0$) which under cooperation results in Pareto-optimal operations (a set of operation rules which cannot be changed to increase one party's gain without decreasing the other party's gain) at point B. In that case, point A is Pareto-inferior. If the current operations are at point B, with no change in the conditions of the problem, the game has no solution ($\Omega = 0$), the parties have no incentive for cooperation, and delaying is a dominant strategy of both players. Under changes in conditions, the new optimal surface may move. The same operations which would have resulted in point B earlier may result in point C due to changes in the problem (e.g. keeping the old operations when fish penalties change, can reduce fish benefits (increase fish losses/penalties). However, under cooperation point C becomes inferior to point D which is the new optimal solution of the bargaining game ($\Omega > 0$) located on the new optimal trade-off curve.

## 5. FERC relicensing and climate change

Climate change is anticipated to increase global temperatures by 1.1–6.4 °C by 2100 [11]. Climate change can result in changes in various conditions such as flow timing and quantity, temperature, biological/ecosystem changes, and fish responses, for FERC projects. Riverine ecosystems of any bioregion are determined by climatic conditions, particularly precipitation and temperature. Changes in precipitation can cause significant changes in riverine plant and animal communities. Various studies [12–16] also have found hydropower operations across the United States to be sensitive to climate change.

License terms are generally fixed until the next license is issued. Operating under changing climatic conditions with the fixed license terms is challenging for operators and may result in revenue

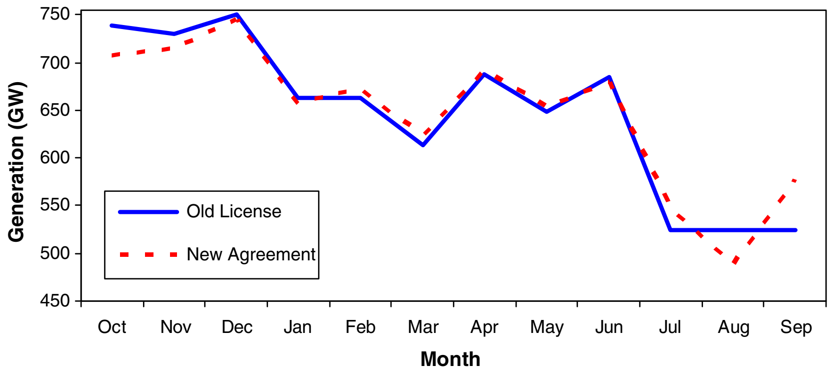

**Fig. 3.** Monthly hydropower generation with new fish penalty weights based on the old license (no-cooperation) and the new agreement (cooperation).

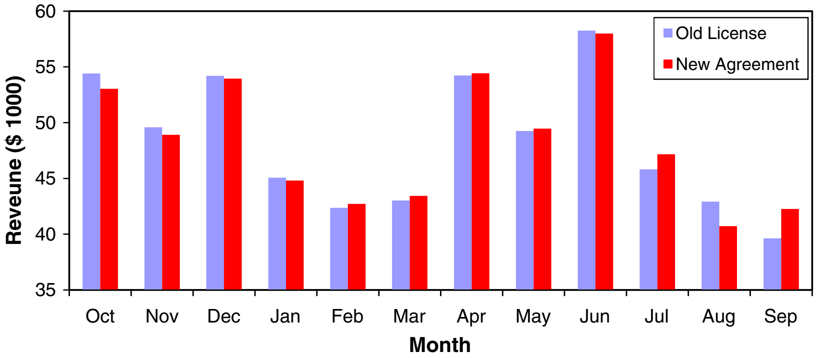

**Fig. 4.** Monthly hydropower revenue with new fish penalty weights based on the old license (no-cooperation) and the new agreement (cooperation).

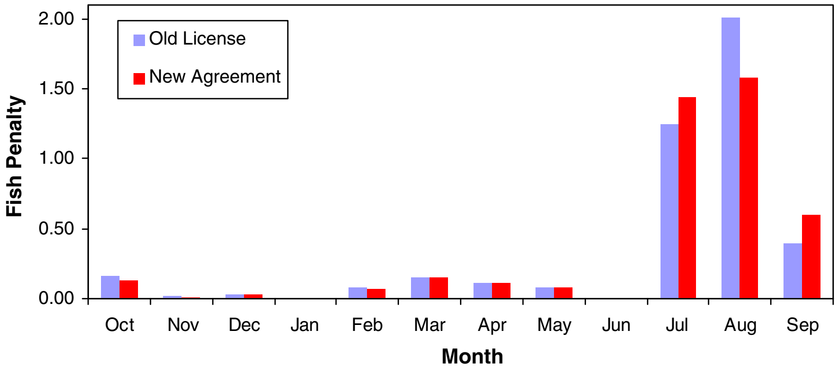

**Fig. 5.** Monthly fish penalties with new fish penalty weights based on the old license (no-cooperation) and the new agreement (cooperation).

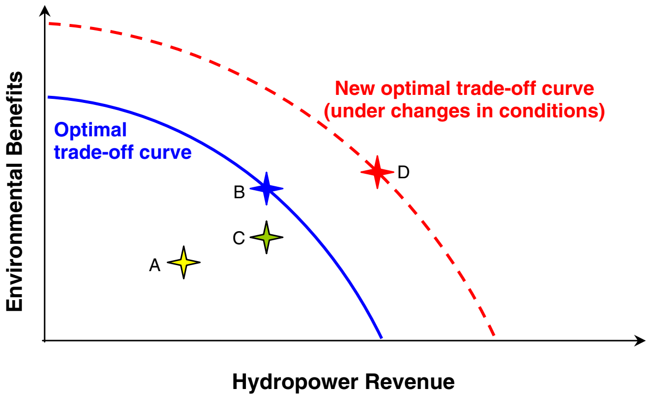

**Fig. 6.** Trade-off between fish penalties and hydropower revenue with old and new conditions.

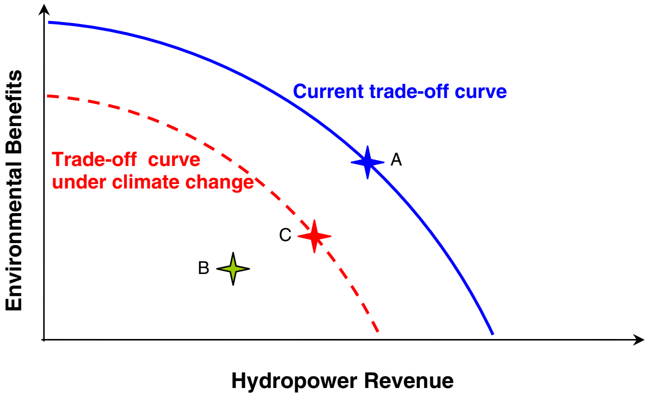

**Fig. 7.** Trade-off between the fish penalties and hydropower revenue with and without climate change.

losses. On the other hand, the environmental constraints available in the license may not maximize environmental benefits under changing conditions as the biological and ecological responses may not be known at the time of license issuance.

The FERC relicensing bargaining model can help determine if climate change could provide an incentive for cooperation of involved parties to speed up the third stage of the FERC relicensing process. Changes in conditions for FERC relicensing may move the optimal trade-off curve (Fig. 7) and make the optimal operations and solution (Point A) based on the conditions of the current license infeasible or suboptimal (Point B). In that case, the bargaining model finds a new optimal solution with $\Omega > 0$ (Point C). Since operations are based on the terms of the current license as long as a new license has not been issued, under hydrologic changes when $\Omega > 0$, delaying (non-cooperation) is not the dominant strategy for the players and both parties are willing to cooperate to minimize losses from delaying the license renewal.

For project A, if the reservoir inflow changes due to climate change (Fig. 8) (assuming that fish penalties and hydropower prices do not change), the hydropower operator responds adaptively by changing the operations (based on the hydropower optimization model (Eqs. (19)–(27))) to minimize the revenue losses due to climate change. Total hydropower revenue and fish penalty before and after climate change are given in Table 5. Reduction of annual inflows by 24% results in a drop in annual revenues by 18% and a substantial increase in fish penalties.

Under climate change, the hydropower operator loses some revenues, but has to keep the operations based on the existing license.

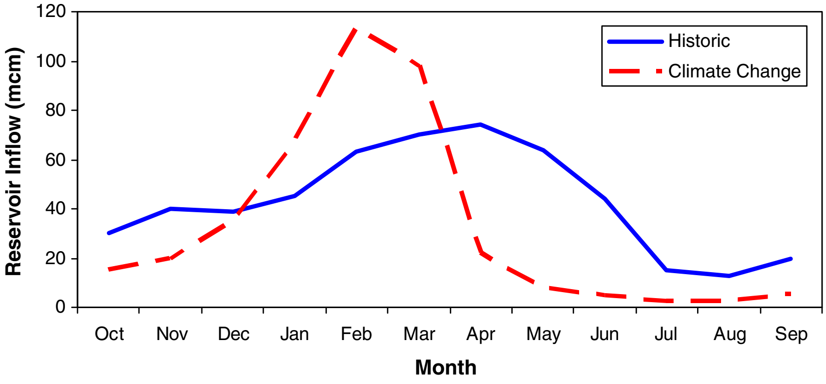

**Fig. 8.** Average monthly inflows to Reservoir A under different climate scenarios.

**Table 5**
Gains of each party under different climate change scenarios.

| Case description | Fish penalty | Hydropower revenue |
|---|---|---|
| Operations based on the existing license (with historic climate) | 3.25 | $ 578,746 |
| Operations based on the existing license (with climate change) | 138.27 | $ 471,735 |
| Operations based on the new agreement (with climate change) | 92.45 | $ 475,504 |

On the other hand, fish penalties will be higher with climate change. Under such conditions, a FERC license with new terms and conditions may improve results for both players under climate change, relative to their results with the old license. When the total hydropower revenue and fish penalty under climate change is used in the FERC relicensing bargaining model and the minimum and maximum instream flow requirements are relaxed, a new solution is found that benefits both players ($\Omega > 0$). Therefore, climate change can be an incentive for cooperation. To minimize losses, both parties are willing to hasten a new license with new terms and conditions for downstream flows. Table 5 shows the total hydropower revenue and fish penalty under climate change when the parties are willing to cooperate. Figs. 9–11 indicate the monthly hydropower generation and the gains of each party under non-cooperative and cooperative cases for climate change. Under cooperation, the hydropower generator is a strategic loser in 4 months, reducing its generation and revenue in exchange for higher generation and revenue in 4 other months, keeping generation and revenue equal the rest of the year with higher overall annual revenues. On the other hand, fish penalties increase/decrease (environmentalists strategically lose/win) whenever hydropower generation increases/decreases, making cooperation desirable for both parties.

## 6. Adaptive FERC license

Climate change may be an incentive to cooperate when the uncertainty about its effects is minimal. Therefore, the projects that are currently in the relicensing process might disregard hydrological and ecological effects of climate change due to the lack of reliable information about the climate. Climate change is expected to become more important in FERC negotiations over the next few decades when its impacts have been experienced and the parties already feel its effects on the system. In the short run, stakeholders may pay more attention to their existing benefits and limit their negotiations to current issues, ignoring long-term conditional changes of the system. The terms and conditions in a FERC license will be valid for the duration of the license (30–50 years) as well as the next relicensing negotiations period (5–21 years beyond the expected expiration of the license). These terms and requirements limit the flexibility of the system to respond to changing conditions, including climate change. Therefore, a framework is suggested for addressing this problem while protecting the rights and basic gains of each party involved in a FERC license.

Although short term licenses may increase the chance of responding to changing conditions and improvement of management based on the new information about the system, the transactions costs and risks of negotiations and the relicensing process can make this solution inefficient. Assuming the length of the FERC license and the relicensing process does not change, parties might be allowed to amend the terms of the license at intervals during

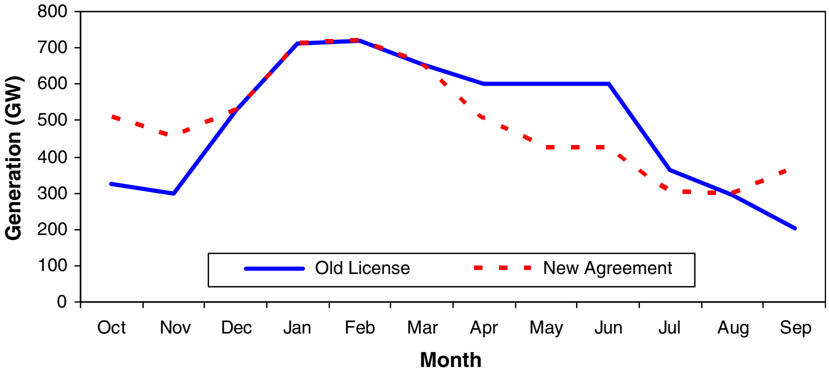

**Fig. 9.** Monthly hydropower generation under climate change based on the old license (no-cooperation) and the new agreement (cooperation).

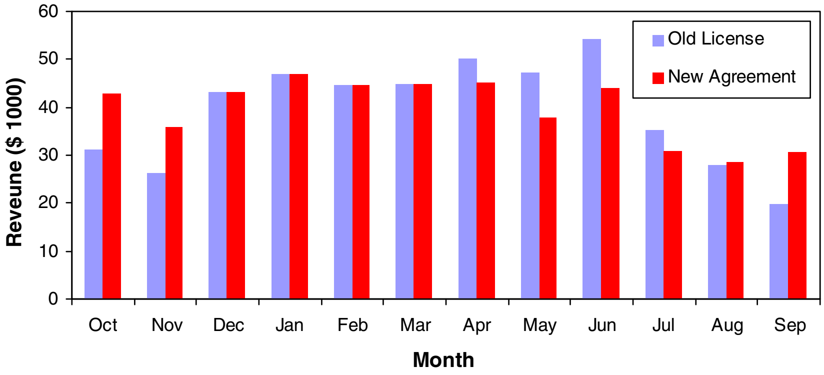

**Fig. 10.** Monthly hydropower revenue with climate change based on the old license (no-cooperation) and the new agreement (cooperation).

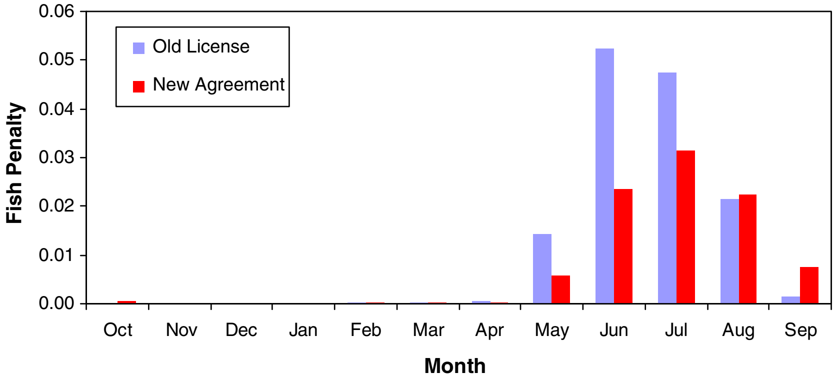

**Fig. 11.** Monthly fish penalties with climate change based on the old license (no-cooperation) and the new agreement (cooperation).

the license period. At the beginning of each interval, parties have two choices. They can either cooperate for changing the license for a limited time to increase gains to all parties, or they can chose to not cooperate and retain the existing license terms. At each interval, parties can use the latest information and calculated gains while bargaining. Cooperation becomes possible when a win–win situation exists and all parties can benefit from the changed terms. The suggested method can increase the flexibility of the system to respond to different changes (e.g. ecological, hydrological, etc.).

In case of project A, let us assume a new license will be issued in 2012, and in the relicensing process climate change is not an initial concern to the parties. This license will be valid until 2042. If in two decades, hydrology changes substantially, the existing terms and conditions may prove infeasible or inferior solution for both parties. If the parties are allowed to amend the license cooperatively, the terms and conditions of the license can be changed slightly when both parties agree that they will gain more under the revised terms. The new terms can be valid for a set time until more information is available and the ecological response is known better. After a set period (say 5 years), the basic terms of the license become valid and the revised terms become invalid. Again, parties can bargain to increase their gain cooperatively for another limited period.

The revision of a license's terms might be done every few years without FERC's involvement (no cost to FERC), to improve the adaptability of the system to changing conditions (most importantly climate change). What makes an adaptive FERC license feasible (in game theoretic terms) is the "no loss factor". No parties can lose from the amendments, as if one party prefers the existing license terms, the license is not changed.

## 7. Conclusions

The study discussed the "strategic loss" concept and suggested revisions to the Nash and Nash–Harsanyi bargaining solutions for application to linked games. Based on the Nash bargaining solution for linked games, this paper explored why in practice FERC relicensing may take longer than expected. A FERC relicensing bargaining model was developed. The developed model, which can support negotiations in stage 3 of the FERC licensing process, can provide insights into FERC relicensing, explain why parties to a FERC license may refuse to cooperate to complete a relicensing process; and find conditions under which cooperation and speeding the relicensing process becomes possible.

The cases discussed in this paper are just numerical examples of theory with many simplifications and assumptions. In practice, estimating the environmental and ecological benefits is controversial and the functions presented here may not be realistic. During the negotiations, the parties can be asked to provide data and functions for utility estimations. Also, in practice, negotiations involve more than two interests, so the modified Nash–Harsanyi bargaining solution, suggested here, should be applied instead of the Nash bargaining solution. This makes the optimization problem more complicated, increasing the computational effort.

Climate change is not expected to enter the FERC negotiations as a major concern at present. However, over time it may provide incentives for cooperation among the parties to FERC relicensing. The fixed terms and conditions of the FERC licenses limit the flexibility of operations to respond to different changes in the systems' conditions. As the effects of climate change are not largely known, an adaptive FERC license is suggested.

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