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Energy, backstop endogeneity, and the optimal use of groundwater

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Abstract

To meet the growing demand for freshwater, many regions have increased pumping of groundwater in recent years, resulting in declining groundwater levels worldwide. A promising development is technical change regarding groundwater substitutes such as desalination and wastewater recycling. However, because these technologies are energy intensive, optimal implementation also depends on future energy price trends. We provide an operational model for the case of reverse-osmosis seawater desalination. In an application to the Pearl Harbor aquifer in Hawaii, we find that allowing the cost of desalination to increase at an average annual rate of 2.4 percent over the next century results in a substantially steeper efficiency price path for water. The higher prices decrease optimal groundwater extraction and induce a slower head drawdown over a longer period of time, delaying the transition to desalination by over 30 years. Because the rise in energy costs exacerbates efficiency losses from under-pricing, any delay in implementing efficiency pricing will cause either a greater future increase in prices or the need for rationing. Reforming prices sooner rather than later may be more politically feasible, given that consumers may be more amenable to a gradual rise in prices today than, say, a sudden doubling or tripling of prices ten years from now. With this foundation, we outline a research agenda for extending the framework to other groundwater substitutes and for adaptation to climate change.

Keywords: Dynamic optimization, endogenous backstop, groundwater management, water-energy nexus

JEL code: Q25

Energy, backstop endogeneity, and the optimal use of groundwater

Renewable resources can be modeled as having a perfect yet costly substitute that is available in unlimited supply -- a backstop resource (e.g. Krulce, Roumasset, and Wilson 1997; Koundouri 2004). Typically, the cost of the substitute resource is regarded as exogenous and constant, even though prices of inputs used to produce the backstop resource may be changing (Farzin 1984).[1] In particular, the backstop technology may be energy intensive and therefore increasingly costly as energy resources become scarcer. On the other hand, technical change (at least partly induced by energy scarcity) is a potentially offsetting force. How can this backstop endogeneity be taken into account in policies governing groundwater extraction and in the planning for resource substitution? In the framework developed in this article, we allow the price of the backstop resource, desalination, to vary over time in response to the combined effect of changes in energy prices and water purification technology.

Groundwater is the world's most extracted raw material – current withdrawal rates are estimated at 982 km^3 per year – and provides 25-40 percent of the global population's drinking water (NGWA 2013). In the United States, groundwater constitutes roughly 20 percent (80 billion gallons per day) of total water withdrawals (USGS 2009) and supplies nearly all municipal water use in some states, such as Hawaii. Since the beginning of the 20th century, groundwater water tables – a water table is the upper surface of subsurface geological material in a given region that is saturated with groundwater – have fallen in many aquifers across the country. For example, areas in the Gulf Coastal Plain have experienced declines of 70-400 feet, areas in the High Plains and Pacific Northwest have seen declines of more than 100 feet, and the Desert Southwest and Chicago-Milwaukee area have faced declines of 300-500 and 900 feet respectively (Konikow 2013). A promising development is technical change regarding groundwater substitutes such as desalination and wastewater recycling. Unfortunately these technologies are energy intensive and energy prices are also expected to continue increasing in the long run. This article aims to extend the renewable resource economics of groundwater to allow for the increasing cost of substitutes and technical change. We provide an operational model for the application to desalination. With this foundation, we suggest a research agenda for extending the framework to other resource substitutes and for adaptation to climate change.

In groundwater economics, the existence of an abundant but costly groundwater-substitute technology, such as desalination, is often assumed. Yet theory and practice, for the most part, have not properly accounted for the energy-intensive nature of water management in determining optimal groundwater extraction profiles. Energy prices will affect optimal water pricing and groundwater extraction rates through two primary mechanisms: pumping costs and production costs of groundwater alternatives.[2] Water scarcity induced by rising per capita incomes and population growth may be compounded in the future by the rising cost of energy-intensive groundwater substitutes. Concurrently, innovation will reduce the share of energy costs in technologies like desalination, although the rate of innovation must eventually decline over time. How these competing effects ultimately alter long run optimal groundwater management strategies will depend on the model's underlying assumptions. To that end, we discuss several energy/innovation scenarios and their resulting effects on optimal water management. In particular, we focus on the case wherein energy scarcity dominates energy-conserving innovation such that the backstop price is increasing in the long run. What are the resulting effects on optimal extraction and pricing, the timing of backstop investment, and the urgency of policy reforms?

Energy prices

From 1994 to 2013, energy prices in the United States rose from 6.4 to 6.9 cents/kWh in the industrial sector, 7.8 to 10.3 cents/kWh in the commercial sector, and 8.4 to 12.2 cents/kWh in the residential sector, which translates to an annual average growth rate of 1.5-2 percent across all sectors (US EIA 2013a). The rate is expected to eventually taper off, however, as fossil fuel and coal generation is increasingly replaced by renewable energy sources. The US EIA (EIA 2013b) projects energy prices to 2040 under three scenarios: (i) a "reference case" that assumes existing laws and regulations remain unchanged, (ii) a "no sunset case" that assumes tax credits for renewable energy sources in the utility, industrial and building sectors are extended, and (iii) an "extended policies" case that includes additional updates to federal equipment efficiency standards. In the reference scenario, the price of electricity is projected to grow at an average annual rate of 2.0%, 1.9%, and 2.2% in the residential, commercial, and industrial sectors respectively. In the alternative scenarios, the increase in growth rate is more gradual. Given the large amount of uncertainty surrounding the conditions that determine future energy prices, we will use the EIA projections as a starting point, and assume that the growth in energy prices are eventually tempered by the increasing substitution of renewable for non-renewable energy and advances in renewable technologies.

Groundwater

Inasmuch as our primary objective is to characterize the effects of energy price fluctuations and induced innovation on water management, we employ a simple single-cell aquifer model, augmented to include discharge that varies with the head level (Krulce, Roumasset, and Wilson 1997).[3] A coastal aquifer is naturally recharged (R) by precipitation in its upstream watershed.

The volume of water stored in the aquifer in any given period is indexed by the head level (h) – the vertical distance between mean sea level and the water table. While recharge adds freshwater to the aquifer, the head level may be drawn down due to both anthropogenic extraction (q) and natural discharge (d). Since coastal aquifers are lenses of freshwater floating on denser underlying seawater, pressure on the edge of the lens causes groundwater to discharge into the ocean. It follows that the discharge function is head-dependent because lens pressure is size-dependent and head is representative of stored freshwater volume. The evolution of the head level over time is described by the following equation:

$$(1) \qquad \dot{h}_t = R - d(h_t) - q_t$$

The cost of extracting groundwater is determined primarily by the energy required to lift water from the aquifer to the surface, where lift (L) is equal to the vertical difference between the ground elevation at the well (e) and the water table. Because the well elevations are fixed, we can write the extraction cost function more concisely as a function of the head level and the price of energy: $c_q(h;p^E)$. Unit extraction cost is a decreasing and convex function of head. As the head level is drawn down, the distance that groundwater must be lifted increases, which naturally requires more energy and results in a higher marginal extraction cost. For a given head level, an increase in the price of energy also increases the unit cost of water extraction. Assuming non-positive second derivatives for $c_q(h;p^E)$ allows for both linear and strictly convex costs. The latter characterization might apply, for example, if existing wells are not sufficient to meet pumping demands in the future even after redistribution of the total load across wells. In that case, construction costs of new wells in the long run could drive up pumping costs non-linearly. Although innovation of pumping technology will reduce extraction costs in the future to some extent, we abstract from that possibility in the discussion that follows.

Desalination

Many types of desalination processes currently exist, and new processes are likely to be developed in the future. Of the existing technologies, reverse osmosis (RO) – a purification technology that typically uses semipermeable membranes to remove salt or effluent materials from water – requires the least total equivalent electrical energy (3.5-5 kWh/m^3) and is also the most popular; in 2011 RO was used in approximately 66% of installed desalination capacity (IDA 2013). For comparison, multi-stage flash distillation (MSF) requires 13.5-25.5 kWh/m^3, multiple-effect distillation (MED) requires 6.5-11 kWh/m^3 and mechanical vapor compression (MVC) requires 7-12 kWh/m^3 (DESWARE 2013). For that reason, we focus attention on projected technological developments in the area of RO research. While RO may be applied to seawater, brackish water, or even wastewater with variable recovery efficiencies, all calculations henceforth will be based on seawater treatment. The methodology is generally applicable, however, provided that cost and technology assumptions are adjusted to match the type of water being treated.

As energy prices continue to rise in at least the short to medium term, energy efficiency of RO may increase due to induced innovation, i.e. the share of RO desalination cost attributed to energy may decline over time. From 1970 to 2008, the power consumption required to produce a cubic meter of desalinated seawater fell from roughly 16 kWh to less than 5 kWh (Elimelech and Phillip, 2011), which corresponds to a 3-4 percent average annual rate of decline. It is important to note, however, that efficiency gains have been steadily declining; from 1970 to 1980, power consumption requirements fell at 10 percent annually, whereas the decline was a modest 3 percent from 2000 to 2008. While it is difficult to project innovation, the historical trend suggests that efficiency gains in terms of energy consumption will continue to slow in the future.

The total cost of RO treatment will also decline with improvements in membrane technology, chemical processes, and machinery, although the rate of decline will eventually decelerate. Since the early 1970s, the cost of producing one cubic meter of desalinated seawater has fallen from \$3 to less than \$1 (Ghaffou, Missimer, and Amy 2013). In some cases (e.g. Ashkelon, Israel and Tampa Bay, USA), desalinated water is being produced for as little as \$0.50 per cubic meter (Greenlee et al. 2009). Within the past decade, however, the unit cost of desalination appears to have rebounded and is currently following a slight upward trend. This may be an indication that rising energy costs are already beginning to dominate advances in desalination technology. We characterize the cost of the backstop technology as a function, $c_b(\alpha,\beta,p^E)$, where the time-varying terms α and β represents induced innovation and general technological advancements in RO respectively.

The water management problem

The objective is to choose groundwater extraction and desalination (b) in every period to maximize the present value of net benefit to society, subject to the aquifer's equation of motion (Eq. 1) and given projections for future energy prices, technological advancements in RO desalination and a positive discount rate (r):

$$(2)\qquad \underset{q_t,b_t}{Max} \int_{t=0}^{\infty} e^{-rt}\left[\int_{x=0}^{q_t+b_t} D^{-1}(x,t)dx - q_t c_q(h_t;p_t^E) - b_t c_b(\alpha_t,\beta_t,p_t^E)\right]dt$$

where D is the inverse demand (marginal benefit) of water, and the area under the inverse demand curve measures benefits from water consumption. Eq. 2 can be solved in an optimal control framework. The necessary conditions for the corresponding current value Hamiltonian can be combined along similar lines as Krulce, Roumasset, and Wilson (1997) and Roumasset and Wada (2012) to derive the following condition for water:

$$(3) \qquad p_t = c_q(h_t; p_t^E) + \frac{\dot{p}_t - c_q'(h_t; p_t^E)[R - d(h_t)]}{r + d'(h_t)}$$

Eq. 3, which states that the marginal benefit (p_t) of water must equal the sum of marginal extraction cost and marginal user cost (MUC). Equation (3) is identical to the standard coastal groundwater case, with both cost terms dependent on the exogenous price of energy. Although induced innovation and other technological advancements do not enter Eq. 3 directly, an additional necessary condition for the maximization problem (Eq. 1) is

$$(4) \qquad p_t \le c_b(\alpha_t, \beta_t, p_t^E) \;\text{ if} < \text{then } b_t = 0$$

Eq. 4 says that if the marginal benefit (efficiency price) of water is less than the backstop cost, using desalination is not optimal. As technological change and the price of energy shift the cost of desalination over time, however, desalination may eventually serve as an optimal supplement to groundwater extraction. As discussed in the following application, when backstop cost as well as energy costs are rising, both factors increase the rate of increase in MUC, thus increasing the rate of increase in efficiency prices.

Application: Pearl Harbor aquifer

The developed framework will be applied to the most heavily used source of groundwater in the state of Hawaii, the Pearl Harbor aquifer. Pearl Harbor is a suitable case study both because it is a large and well-studied coastal aquifer and because RO seawater desalination is a natural backstop candidate for an island like Oahu. However, the methodology is transferable to other regions, inasmuch as mounting water scarcity and rising fossil fuel prices are phenomena observed worldwide. We begin by incorporating what we feel is the most likely backstop cost scenario – taking into account both projected energy and innovation trends – into a standard coastal groundwater optimization model. We then discuss other possibilities in which either the energy price or technology effect dominates over some period before eventually approaching a constant level in the very long run.

Hydrological, cost, and demand equations and parameters follow Krulce, Roumasset, and Wilson (1997) and are summarized in table 1. Evolution of the head level over time, described by Eq. 1, is determined by a combination of recharge, natural discharge to the ocean, and extraction. The objective of the management problem is to choose extraction and desalination in every period to maximize present value, where present value depends on benefits – measured as the area under the inverse demand curve – as well as costs, including those incurred by both groundwater extraction and desalination.

Table 1. Equations and Parameters

Description	**Equation/value**	**Units**
Conversion factor (head to volume)	78.149	Billion gallons/foot
Initial head level	15	Feet
Initial backstop cost	3	Dollars/thousand gallons
Recharge	281	Million gallons/day
Discharge	$0.24972h^2+0.022023h$	Million gallons/day
Unit extraction cost	$0.283(15/h)^2$	Dollars/thousand gallons
Demand	$186.2e^{\cdot 02t}(p+0.947)^{0.3}$	Dollars/million gallons

We now assume that the backstop cost is changing over time. The unit cost of seawater desalination is influenced by the price of energy and innovation in desalination technology. Technological change may be dominating rising energy costs currently, but gains in energy efficiency have slowed considerably in recent years. Although future increases in energy prices are likely to be tempered by more substitution toward renewable energy sources, it appears that the scarcity effect of energy sources will dominate innovation in the foreseeable future, although the subject of when (if ever) the forces of resource depletion will overcome those of technological progress is a seemingly never ending debate (Krautkraemer 1998; 2005).

In the long run, we expect that the unit cost of desalination approximately approaches a constant. Technological progress in the backstop, RO desalination, has already started to slow and is likely to decline asymptotically toward a constant long-run cost (Fischer and Salant 2012). At the same time, the fraction of petrochemicals used to power the RO process is asymptotically approaching zero as renewable energy alternatives (e.g. photovoltaics) become cost-effective. Consequently, the energy cost component of desalination is increasing, concave, and bounded from above. To illustrate the two opposing forces, we consider an outer bound for the backstop cost of $30 per thousand gallons. (This tenfold increase corresponds to an average annual increase of 2.4% over 100 years.) Since the energy effect appears to already be dominating the innovation effect, we fit an upward sloping curve between the backstop costs at year 0 and year 100: $3.00523 + 0.0837046t + 0.00558572t^2 - 0.0000372381t^3$. This illustrates the case where the rate of cost increase is eventually declining due to substitution of more abundant nonrenewable and renewable energy sources (Chakravorty, Roumasset, and Tse 1997).

The solution method is to first calculate the optimal steady-state head level (h^*) based on the long-run backstop price (c_b^*). The terminal time (T^*) is then solved for, such that the solution to

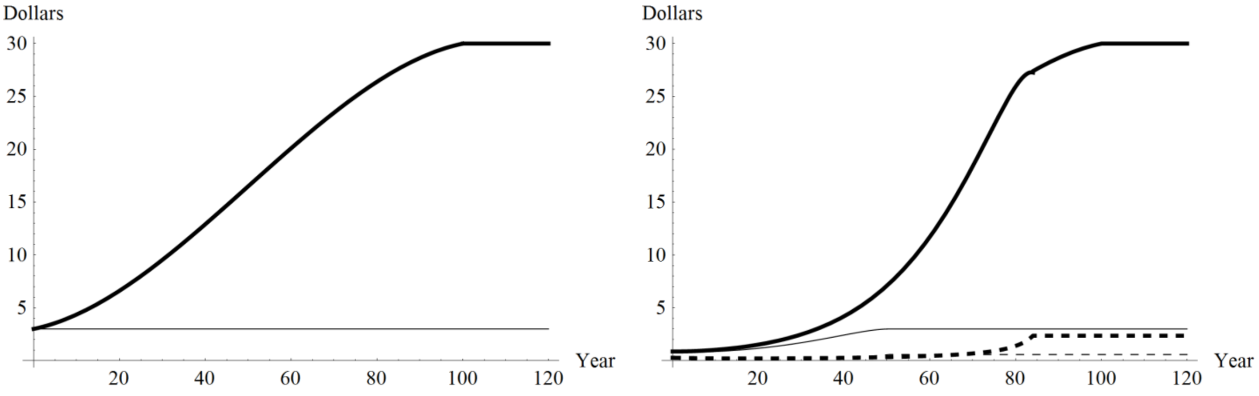
Eqs. 1 and 3 with terminal conditions $p(T)= c_b*$ and $h(T)=h*$ results in $h(0)=h_0$. If the optimal price path for water does not reach the backstop price by year 100, then the solution is the same as if the backstop price were constant at the year-100 level. If instead the candidate optimal price path reaches the year-100 backstop price prior to year 100 and then experiences a discreet jump downward, then it must be optimal to switch to the backstop sooner. In that case, move the endpoint toward the present, i.e. use the backstop cost corresponding to an earlier period (e.g. year 99) and calculate $h*$ again. Use the new terminal values c_b* and $h*$ to calculate the optimal paths. Keep adjusting the guess for the switch-point until the price no longer jumps.

To illustrate the effect that a variable backstop cost has on the optimal solution, we compare our findings with Krulce, Roumasset, and Wilson's (1997) original results (figure 1). When the backstop cost is allowed to rise, desalination is delayed for over 30 years, from year 50 in the constant cost case to year 84. Because the price curve is steeper, the head level is drawn down more slowly and over a prolonged period of time, although the long run head level turns out to be lower than in the constant cost case. Note that even a tenfold increase in the ultimate backstop cost has very little effect on the full marginal cost today, thus requiring only small current adjustments to pricing schedules, provided that efficiency pricing has already been implemented. In one sense, this increases the urgency of switching to efficiency prices now, given the political difficulty of large increases later.[4] That is to say, consumers may be more amenable to a gradual increase in prices starting immediately than to a sudden doubling or tripling of prices ten or twenty years from now.

While we believe that an upward sloping, eventually concave, backstop price curve is probable in this particular scenario, one could imagine situations where the starting point is on the left side of a u-shaped backstop price curve or the technology effect always dominates, i.e.

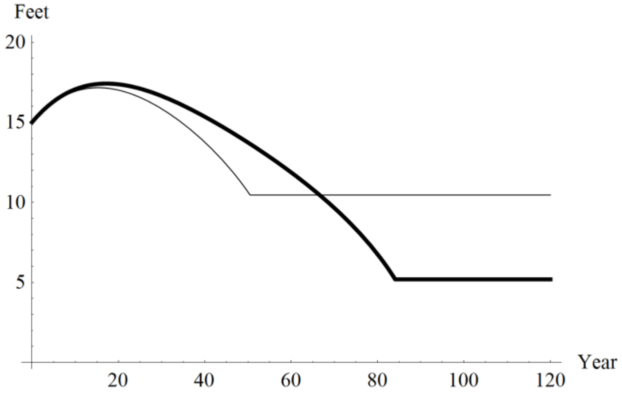
the backstop price is always declining. The latter case is especially of interest, inasmuch as the long run implication is that the resource (if renewable) would be allowed to replenish. Once the efficiency price for water reaches the backstop price curve, it must decline at the same rate – otherwise it would only make sense to use the resource with the lower price. And a declining price schedule corresponds to an increasing head trajectory for the aquifer. Depending on the parameters of the particular application, the steady state head level may end up at or above its initial level.

Figure 1. Backstop price, efficiency price, and optimal head paths



(a) Backstop price

(b) Efficiency price and extraction cost



(c) Optimal head level

Note: The steeper price path with rising backstop costs (heavy solid curve) delays the implementation of desalination but the head level is ultimately drawn down further than in the constant backstop case (light solid curve). Dashed lines are extraction costs in the two scenarios.

An important caveat to the results discussed is that we abstracted from energy costs and innovation in groundwater extraction to highlight the effects of a variable backstop cost. The inclusion of energy and technology trends for groundwater pumping increases the complexity of the management problem, but examining the tradeoffs introduced sheds some light on possible outcomes. Rising energy prices have the same qualitative effect on both resources in that it makes them more expensive. However, the quantitative impact depends on how energy intensive pumping is versus desalinating. Similarly, innovation reduces the price for both resources, but the rate of innovation, as well as the location on the projected innovation curve, will determine which resource sees a greater decline in cost due to technological improvements. As an example, suppose that innovation has stagnated for groundwater pumping, but that like desalination, pumping is very energy intensive. As the price of energy goes up, both resources become more expensive, but the effect on desalination is tempered by innovation. Consequently, the price of water rises to the backstop cost sooner and the aquifer drawdown period is shortened.

Another caveat is that the model is developed under the assumption that the minimum head constraint for the aquifer is not binding, and results from the simulation suggest that this assumption is valid for our particular application. In general, an aquifer's depth is bound from below by impermeable material in the case of an inland aquifer or non-potable sea water in the case of a coastal aquifer. In either case, there is a corresponding minimum allowable head level, beyond which extracted water is of unacceptable quality. If the constraint is binding in the optimal solution, the head level may reach its maximum sustainable yield level before desalination is used or after desalination is used but before the steady state, wherein the backstop price stabilizes at a constant level.

In areas where climate change is expected to reduce total annual rainfall and/or increase the occurrence of heavy rainfall events with drier periods in between, natural groundwater recharge will likely decline in the future. The resulting pressure on water scarcity will exacerbate the effect of rising energy prices. That is, the efficiency price of water will rise even more rapidly in the face of climate change, further increasing the urgency of price reform. Thus adaptation to climate change in the form of water price reform should account for changing energy prices and innovation, just as management of a resource with an endogenous backstop should account for the scarcity induced by climate change.

Concluding remarks

Groundwater is a renewable and replaceable resource in the sense that it displays a positive and concave growth function, decreasing unit extraction cost as a function of stock, and can be partially replaced by desalination, an abundant yet costly substitute. In the standard solution for a coastal aquifer, a generalization of the inland aquifer model, the steady state extraction rate is given by the equality of the backstop price and the sum of extraction cost and marginal user cost. The remaining consumption is provided by the backstop resource. The problem with this formulation is that energy costs, an important component of the cost of desalination, are likely to be rising. Moreover the canonical solution omits technological change, in particular with respect to the backstop cost.

Accordingly, we extend the basic renewable resource model to allow for a changing backstop price, which evolves according to assumptions about energy costs and technological progress regarding the backstop, and illustrate an algorithm for solving for efficiency prices and quantities over time. As an outer bound, we consider the case of a 10-fold increase in desalination cost, which corresponds to an average annual increase of 2.4% over 100 years. In this particular example, we find that allowing for increasing energy costs results in more rapidly increasing efficiency prices, which decrease optimal extraction and delay the transition to the backstop by over 30 years. The steeper efficiency-price curve induces a slower head drawdown over a longer time period such that it takes roughly 15 years longer to reach the head level where desalination is first employed (10.5 feet). Unlike the case of constant desalination cost however, the head level continues to fall in the long run, as it approaches the optimal steady state level of approximately 5 feet.

One important policy implication is that rushing to implement a backstop, e.g. to sustain the extracted resource stock near current levels, will result in unnecessary welfare losses. In our application, we find that rising energy costs can delay the optimal transition to desalination on the order of decades. Because the rise in energy costs exacerbates efficiency losses from under-pricing, particularly in the medium and long term, any delay in implementing efficiency pricing will cause either a greater future increase in prices or the need for rationing. Yet, even a tenfold increase in the backstop cost over 100 years has very little effect on the full marginal cost of water today. This implies that rising energy costs make pricing reform only slightly more urgent than without taking those costs into consideration. Nonetheless, reforming prices sooner rather than later may be more politically feasible. Consumers may be more amenable to a gradual rise in prices starting immediately than, say, a sudden doubling of the price ten years from now. Making these benefits transparent will also enhance the political feasibility of reform.

Given that the simulation abstracted from technological change in groundwater extraction, the results (relative to the baseline optimization scenario) were driven primarily by the exogenous price path of desalination. More generally, innovation may reduce the cost of both groundwater extraction and desalinated water, although the rates of decline will differ. One extension would be to treat energy efficiency in each sector as both induced by changes in energy prices and directed by sector-specific research and development (R&D). The extended framework could be used to derive implications for said R&D effort. Given that pumping costs are low relative to the scarcity value of water, it is possible for the innovation effects for desalination to dominate, even if temporarily.

Although we assumed that the backstop cost is rising over time, it may be the case that technological innovation always dominates the energy price effect. If the backstop price were indeed declining over time, the resource would begin to replenish once the efficiency price of water and the backstop price converged. In general, the backstop price may be increasing or decreasing at any given point in the future, depending on advances in the backstop technology as well as energy prices.

This perspective reveals an important research agenda for managing our increasingly scarce groundwater resources. First, we need better estimates of how the interplay of energy costs and innovation are likely to play out over time. To the extent that these estimates portend substantial increases in efficiency prices, this warrants increased attention to institutional mechanisms for implementing said prices at the margin (e.g. adjusting block-pricing schedules). In the present study we have only considered the effect of a changing backstop price on water management. But clearly other partial substitutes for groundwater are available, most notably watershed conservation and the use of recycled wastewater. To the extent that these partial substitutes are economically viable, they may be capable of dramatically delaying the time at which the steady state solution is reached and accordingly substantially reduce the rate of increase in the full marginal cost. Resource economics needs to be extended to allow for the simultaneous solution for these different instruments of management, including the time path of investment in both infrastructure and natural capital. Implementing these models will require advances in integrated models of economics, engineering, and watershed hydrology.

References

Chakravorty, U., A. Leach, and M. Moreaux. 2012. “Cycles in Nonrenewable Resource Prices with Pollution and Learning-by-Doing.” *Journal of Economic Dynamics and Control* 36:1448-1461.

Chakravorty, U., J. Roumasset, and K. Tse. 1997. “Endogenous Substitution among Energy Resources and Global Warming.” *Journal of Political Economy* 105:1201-1234.

Elimelech, M., and W.A. Phillip. 2011. “The Future of Seawater Desalination: Energy,

Technology, and the Environment.” *Science* 333:712-17.

Encyclopedia of Desalination and Water Resources (DESWARE), 2013. Energy Requirements of Desalination Processes, http://www.desware.net/desa4.aspx. Accessed 10-28-13.

Farzin, Y.H. 1984. "The Effect of the Discount Rate on Depletion of Exhaustible Resources." *Journal of Political Economy* 92:841-51.

Fischer, C., and S. Salant. 2012. “Alternative Climate Policies and Intertemporal Emissions Leakage: Quantifying the Green Paradox.” Resources for the Future Discussion Paper RFF DP 12-16.

Ghaffour, N., T.M. Missimer, and G.L. Amy. 2013. “Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability.” *Desalination* 309:197-207.

Greenlee, L.F., D.F. Lawler, B.D. Freeman, B. Marrot, and P. Moulin. 2009. “Reverse osmosis desalination: Water sources, technology, and today’s challenges.” *Water Research* 43:2317-48.

International Desalination Association (IDA), 2013. IDA Desalination Yearbook 2012-2013.

Konikow, L.F. 2013. “Groundwater depletion in the United States (1900-2008).” U.S. Geological Survey Scientific Investigations Report 2013-5079.

Koundouri, P. 2004. "Current Issues in the Economics of Groundwater Resource Management," Journal of Economic Surveys, 18:703-740.

Krautkraemer, J.A. 1998. “Nonrenewable Resource Scarcity.” *Journal of Economic Literature* 36:2065-2107.

Krautkraemer, J.A. 2005. “Economics of Natural Resource Scarcity: The State of the Debate.” Resources for the Future Discussion Paper 05-14.

Krulce, D.L., J.A. Roumasset, and T. Wilson. 1997. “Optimal Management of a Renewable and Replaceable Resource: The Case of Coastal Groundwater.” *American Journal of Agricultural Economics* 79:1218-28.

National Groundwater Association. 2013. “Facts About Global Groundwater Usage.” NGWA Factsheet, 9-2013.

Oren, S.S., and S.G. Powell. 1985. “Optimal Supply of a Depletable Resource with a Backstop Technology: Heal’s Theorem Revisited.” *Operations Research* 33:277-292.

Pitafi, B.A., and J.A. Roumasset. 2009. “Pareto-Improving Water Management over Space and Time: The Honolulu Case.” *American Journal of Agricultural Economics* 91:138-53.

Roumasset, J.A., and C.A. Wada. 2012. “Ordering the extraction of renewable resources: The case of multiple aquifers.” *Resource and Energy Economics* 34:112-28.

United States Energy Information Administration. 2013a. Analysis & Projections - Table 2: U.S. Energy Prices, http://www.eia.gov/forecasts/steo/tables/?tableNumber=8#. Accessed 10-30-13.

United States Energy Information Administration. 2013b. “Annual Energy Outlook 2013 with Projections to 2040.”

United States Geological Survey. 2009. “Estimated Use of Water in the United States in 2005.” U.S. Geological Survey Circular 1344, October 2009.

Footnotes

[1] Oren and Powell (1984) consider the cases of a falling backstop cost due to learning-by-doing and backstop uncertainty in the context of a nonrenewable resource. See also Chakravorty, Leach, and Moreaux (2012) and Fischer and Salant (2012).

[2] Transmission costs may also be important, especially in areas where a substantial portion of pumped groundwater is sent to higher elevations.

[3] The canonical interior aquifer model, i.e. in which discharge is negligible or not stock-dependent, is a special case of this one.

[4] The political feasibility of higher marginal charges can also be enhanced by compensating current and near term users with lower prices for inframarginal blocks. The compensatory transfer can be financed via bonds out of the benefits to future consumers from delaying the use of the expensive backstop technology (Pitafi and Roumasset 2009).