Can we afford ocean desalination to double fresh water supply for the coming 13 billion people to live on a hot planet?

A preliminary assessment by B. Grant Logan,
who is seeking a partner in further exploring this critical question. June 26, 2007

Preliminary conclusions from a world ocean desalination model:

(1) Doubling world water supply by desalination (Fig.3) would require an *additional ~3 to 6 TW_e (Terawatts) of electric power consumed by ~2500 large desalination plants worldwide, each plant consuming ~2 GW_e (Gigawatts) each* and *producing 3.6 million m^3 (~ 1 billion gallons) water per day per desalination plant.* This is 2 to 4 times more total electricity than is now produced by the world for all other uses. Since most of this water will be needed for irrigation to supplement rainfall as now used for crops, up to 40% of this total power would be needed just for pumping water inland up to 2000 km from coastal areas. Corollary: as global warming is predicted to constantly shift regions of rainfall and drought over similar large geographic scales, *1-2 TWe will be needed just for extensive water re-distribution even without added water produced by ocean desalination. Local water conservation is always helpful, but not alone a sufficient solution for worldwide water needs, especially for a doubling of the world's population.*

(2) Ocean desalination will likely force a tight linkage between affordability of energy and the affordability of water, as the most efficient water desalination process by reverse osmosis uses electric pumps to force water through membranes at high pressure. If the world could afford to spend no more than 7% of its total Gross Domestic Products for desal water, the same as it spends currently for all forms of energy production, then a *cost of electricity less than 3 cts/kW_ehr (half to a third of most US rates)*, would be required to affordably double the world's total fresh water supply by ocean desalination. *This is a very challenging electricity cost target for any sustainable electricity option that can also provide the huge required power levels.* Much research and development remains to be done before we can know which primary energy sources might meet these demanding needs, even while we should continue to encourage water conservation.

**(3) Ocean desalination, like biomass-derived energy, will also link affordability of energy and affordability of food. Of the assumed doubling of water supply by desalination, 70% is targeted for increasing food supply for a doubling of the world's population, but this does not allow for more water for more biomass to be converted to fuel energy. A simple analysis (see last page) shows that energy derived from biomass, even assuming much more efficient biomass energy conversion (e.g., for biofuel for diesel pump engines), *could not provide sufficient energy to desalinate the same amount of water consumed in growing the plants.* Biomass-derived fuel energy can still play a role in meeting part of the world's fuel energy needs in areas with sufficient rainfall, but not for supplemental ocean desalination itself. *Thus massive, inexhaustible, non-carbon emitting, non-biomass (and affordable) sources of electricity must ultimately be developed if ocean desalination is to double the world's supply of fresh water -a very tall order!*
By affordable is meant no more than 7 % of world GDP to be used for desal water- same as for all energy production. Any more spent on water implies less GDP available for other human economic development. See discussion of energy options for desalination water on the last page.**

Motivation for this study

Of trend setting it is often said "As California, goes, soon goes the nation". By extension, one might add "and so goes the world". Many recent news articles suggest that California may be soon be greatly expanding ocean desalination to supplement coastal city water supplies. One such article by Paul Rogers of the San Jose Mercury News (June 3, 2007) titled "State faces Sea Change to get Drinkable Water" says that "Desalination is costly, but California proposes 20 projects to supply growing need". Perhaps California is wealthy enough to afford ocean desalination using 10 cents per kWe-hr electricity, but what can the other 6.6 billion people on earth afford, hundreds of millions of whom already don't have enough clean water to drink? What happens to them as glaciers melt and global warming progresses? And what about water for food? Anyone who has seen the low levels of Lake Powell and Lake Mead from airplanes can't help but wonder how agriculture in the US southwest can be sustained for very long -similar situations can be found worldwide. Take a look at some sobering numbers in Table 1 below.

Table 1: Basic facts (source Internet-Google key words in left column)

Population (2007)	World	$6.6 \cdot 10^9$	US	$3 \cdot 10^8$	people
Primary energy use (2005)	World	405	US	105	Quads Q (10^{18}J)/yr
Per capital energy use (1995)	World	61	US	350	GJ / person/yr
Total electricity use (2007)	World	33	US	13	Quads electric Q_e/yr
Per capita electricity use	World	5	US	43	GJ_e /person/yr
GDP (2006)	World	48	US	13.2	$T/yr
Per capita GDP (2006)	World	7300	US	44000	$ /person/yr
Primary energy cost @$8.5B/Q	World	3.4	US	0.9	$T/yr
Fraction of GDP for primary E	World	7.1	US	6.8	%
Electricity cost @0.1$/$kW_e$hr	World	0.92	US	0.36	$T/yr
Fraction of GDP for electricity	World	1.9	US	2.7	%
All water usage*: domestic, industrial and agriculture.	World	3720	US	477	km^3/yr **agriculture is 70% of use. All rainfall is 15 x usage.*
Domestic only water use:	World	370	US	61	km^3/yr
Per capita domestic water use	World	$\frac{56}{40}$	US	$\frac{203}{146}$	$\frac{m^3/yr/person}{gal/day/person}$
Max limit to affordable water cost if equal GDP fraction=7% spent for <u>all water as for all energy</u>	World	$\frac{0.91}{0.35}$	US	$\frac{1.9}{0.72}$	$\frac{\$/m^3}{cts/gal}$
At this limit, average monthly water bill for a family of four:	World	17	US	130	$/month

Local per capita water usage vs water development needs can vary several-fold between developed and undeveloped countries. Developing countries like India and China can improve water-conserving agriculture methods, but more water is still needed to increase their water per capita up to the levels of developed countries. Developed countries can clearly reduce water consumption more through conservation and recycling. However, its unlikely that improved agriculture and conservation can, by itself, suffice for a likely doubling of the world's population over the next 50 years. Much of the world's large urban populations are near major rivers and near coastal areas. Global warming is predicted to melt glaciers feeding the rivers, and foster droughts in some areas, causing water shortages with uneven geographical impacts. Thus its reasonable to assume a likely need, if not a necessity, for desalination of ocean water on a scale commensurate with current water usage (all forms) of 3700 km^3/yr, *assuming the population doubles.* The high pressures required by reverse osmosis (the most efficient desalination process) and water pumping for inland delivery, are mostly driven by electric pumps, and so this prompts the the question of what limits are placed on cost-of-electricity CoE by the "water affordability limit" given in Table 1 above -see model below.

A plausible model for future cost of water delivered from coastal desalination.

The cost of water (CoW in $/m^3$ water) for reverse-osmosis desalination plants (see Figure 1 below) depends both on the size (plant capacity Q_p, units of m^3 water per plant per day), which determines the economy-of-scale for the unit capital cost, the salinity factor S (S= 1 highest for ocean water. S can be as small as 0.35 for brackish delta water: lower salinity = lower osmosis pressure= lower pump power required), the cost of electricity CoE (in $/kW_e$hr), and the average distance d (km) from the desalination plants to delivery points. Electricity runs the pumps needed to force the salt water through the membranes at high pressures, with an efficiency of pump electric power = 7.2*S (kW_ehr per m^3 water), @ 50 % electric to hydraulic (PV) work efficiency, and for double passes. *Note that the basic energy intensity of reverse osmosis is much less than for distillation.* The osmosis PV energy @ 1000 psi pressure is 6.7 x 10^6 J/m^3 x 2 passes = 13 MJ/m^3 of hydraulic energy, or 26 MJ of pump electrical energy @ 50 % pump efficiency, or 65 MJ of thermal energy before 40% conversion to electricity for pumps. By contrast, distillation would take 2.3 GJ of heat to vaporize 1 m^3 of water at 2260 J/g, and even if one used 90% recuperative heat exchangers, distillation would still require 230 MJ of thermal energy input, still four times more than for the reverse osmosis process.

Quotes from the June 3 article in SJMN/CCTimes news article reverse osmosis desalination costs 2700 to 1000 $ per acre foot = 2.2 to 0.8 $/m3, depending on salinity factor S. (One acre-foot = 1233 m^3 = 325,000 gallons). The typical scale of plant quoted is 15 million gallons per day capacity, and the current bay area cost of electricity at industrial rates is 0.11$/$kW_e$hr. Note that the "affordable limit" cost for water based on 7% of GDP given in Table 1 above corresponds to reasonable costs for domestic water use, but this is still 10 to 20 times the average cost of water used in the world for agriculture (< 0.1 $/$m^3$ ~ mostly cost of storage and delivery). Current water costs for irrigation are basically storage (amortized cost of dams) and distribution/ canal delivery costs to fields, which varies with distance. For desalination plants near coastal areas and river deltas, plant output is located close to city end-use (domestic and industrial uses). The bay area desalination water costs in the SJMN/CCTimes article assumed the plants operate only to supplement city water supply when drought conditions occur, so the quoted costs do not likely imply significant new delivery costs, assuming existing local city water pipelines can be used. However, for the future, when ocean/delta water desalination is assumed to supply water for more inland cities and for agriculture, delivery costs can become significant and depend on distance and average elevation changes from sea level to inland destinations (ave ~ 1 m elevation per kilometer inland).

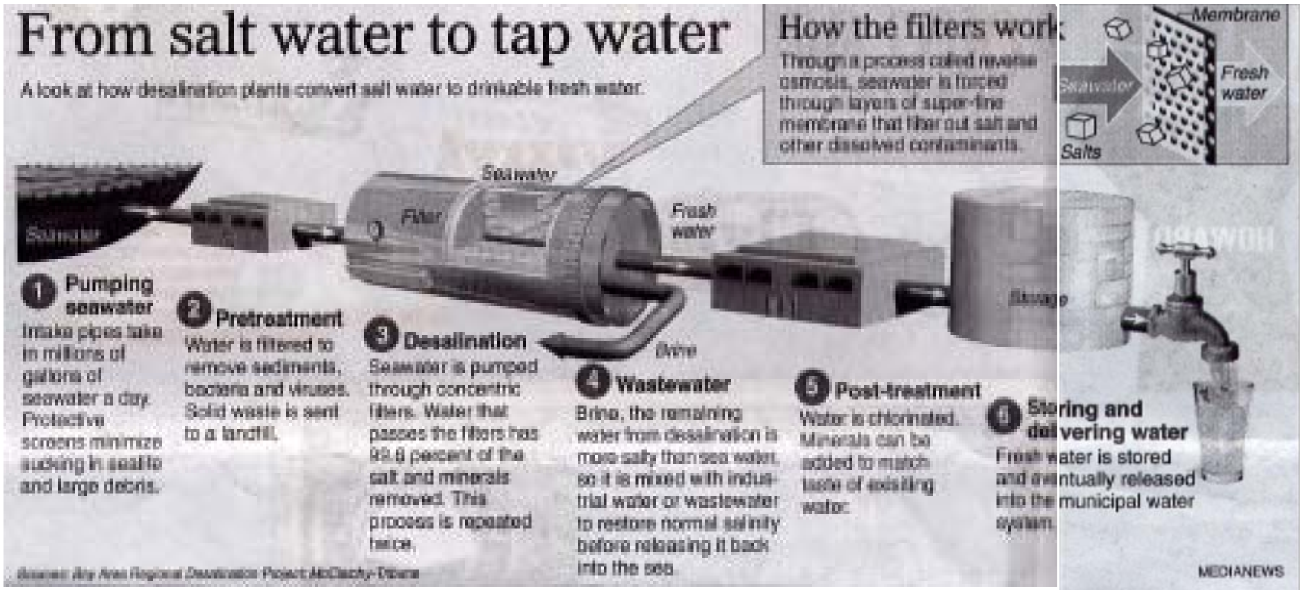

Figure 1: Reverse Osmosis Process Desalination (from June 3, 2007 SJMN/CCTimes)

The unit cost of desalination has fallen steadily as the average desalination plant capacity (in m^3/day) has steadily grown from 6 million gallons per day per plant to now over 60 million gallons (2.5×10^5 m^3) per day per plant recently, as the world's total desalination capacity has grown to over 2.7 billion gallons (10^7 m^3) per day worldwide. That's still only 3.7 km^3 water produced per year worldwide, less than 1 percent of world domestic water use (see Table 1), and less than 0.1 % of present total world water use, so many e-foldings of growth remain for desalination to double the world's supply of fresh water. The cost model assumes the growth in plant size and decrease in unit costs to continue with growth in total world desalinated water output Q_{tot} (in m^3/day).

$$Q_p(Q_{tot}) := 5.7\cdot 10^4\cdot\left(\frac{Q_{tot}}{10^7}\right)^{0.6}$$ m^3/day per plant **Eq. 1**

Unit Cost of Capital (amortized) $$UCoC(Q_{tot}, S) := 1.4\cdot S\cdot\left(\frac{5.7\cdot 10^4}{Q_p(Q_{tot})}\right)^{0.7}$$ \$/m3 **Eq. 2**

Scales with size (capacity in m^3/day)$^{-0.7}$ and with pressure (salinity factor S). Unit Cost of Pumping (UCoP) through osmosis membranes at the plant ***(assumed constant running at max capacity)***

$$UCoP(CoE, S) := 7.2\cdot S\cdot CoE$$ \$/m3 **Eq. 3**

Scales with pressure (salinity factor S) and unit Cost of Electricity (CoE in \$/kW_ehr). The Unit Cost of Delivery (UCoD) can be estimated from pumping energy =mgh increasing with average continental elevation slopes going inland ~ 10^{-3} with approximate equal viscosity losses (both linear in d):

Cost of Delivery $$UCoD(CoE, d) := (0.4 + 4\cdot CoE)\cdot\left(\frac{d}{1000}\right)$$ \$/m^3 **Eq 4**

The first term in Eq 4 is for the cost of concrete conduits for transport, and the second term is the estimated electricity cost for pumping 1 ton/m^3 water with distance d in km, assuming an average elevation change going inland directions of 1km vertical per 1000 km horizontal (this is an underestimate of the rate of elevation change in the US west, but an overestimate in the US east. Average elevation changes with distances from nearest coastlines are roughly similar on other continents).

The Unit Cost of Water (UCoW) is the sum of Eqs 2, 3, and 4:

$$UCoW(Q_{tot}, S, CoE, d) := UCoC(Q_{tot}, S) + UCoP(CoE, S) + UCoD(CoE, d)$$ \$/m3 Eq. 5

For the conditions of the Bay Area desalination plant water prices quoted above (15 million gallons/day = 57,000 m^3/day/plant (Q_{tot} =10^7 m^3/day worldwide), 20 km delivery)

S=1: $UCoW(10^7, 1, 0.11, 20) = 2.2$ S = 0.35: $UCoW(10^7, 0.35, 0.11, 20) = 0.8$ Benchmarks-OK with SJMN/CCTimes quotes. (All units in \$/m^3 water)

$UCoC(10^7, 1) = 1.4$ $UCoC(10^7, 0.35) = 0.5$

$UCoP(0.11, 1) = 0.8$ $UCoP(0.11, 0.35) = 0.3$

$UCoD(0.11, 20) = 0.017$ $UCoD(0.11, 20) = 0.02$

Total world electrical power for both osmosis and delivery

$$Pe_{tot}(Q_{tot}, S, d) := Q_{tot} \cdot \left(7.2 \cdot S + 4 \cdot \frac{d}{1000}\right) \cdot \frac{3.6 \cdot 10^6 \cdot 10^{-12}}{24 \cdot 3600}$$ (TWe) Eq. 6 (total)

Osmosis plant electrical power

$$Pe_p(Q_{tot}, S, d) := Q_p(Q_{tot}) \cdot \left(7.2 \cdot S + 4 \cdot \frac{d}{1000}\right) \cdot \frac{3.6 \cdot 10^6 \cdot 10^{-9}}{24 \cdot 3600}$$ (GWe) Eq 7 per plant

$ORIGIN := 1$

Using Eq 5, lets explore the unit cost of water as functions of world capacity up to 1000 times current production levels (up to 10^{10} m^3/day, enough to double world fresh water supply) and as a function of the average world cost of electricity (in units of \$/kW_ehr). Assume that the total world water use from ocean desalination (S=1) could scale linearly with distance d from coastal desalination plants, reaching 10^{10} m^3/day (3700 km^3/yr) covering an area up to 2000 km from any coast.

For various world production levels $Qtot_i$ $i := 1..10$ $d_i := 20 \cdot i^2$ $Qtot_i := 10^{10} \cdot \frac{d_i}{2000}$

and for Costs of Electricity CoE_j $j := 1..7$ $CoE_j := \frac{1 + 0.2 \cdot 2^j}{100}$ $U_{CoW_{i,j}} := UCoW(Qtot_i, 1, CoE_j, d_i)$

$Qtot_i =$	$Q_p(Qtot_i) =$	$d_i =$
$1 \cdot 10^8$	$2.3 \cdot 10^5$	20
$4 \cdot 10^8$	$5.2 \cdot 10^5$	80
$9 \cdot 10^8$	$8.5 \cdot 10^5$	180
$1.6 \cdot 10^9$	$1.2 \cdot 10^6$	320
$2.5 \cdot 10^9$	$1.6 \cdot 10^6$	500
$3.6 \cdot 10^9$	$1.9 \cdot 10^6$	720
$4.9 \cdot 10^9$	$2.3 \cdot 10^6$	980
$6.4 \cdot 10^9$	$2.8 \cdot 10^6$	1280
$8.1 \cdot 10^9$	$3.2 \cdot 10^6$	1620
$1 \cdot 10^{10}$	$3.6 \cdot 10^6$	2000

World m^3/day Plant m^3/day km

$j =$	$CoE_j \cdot 10^2 =$
1	1.4
2	1.8
3	2.6
4	4.2
5	7.4
6	13.8
7	26.6

cts/kW_ehr

$\frac{\$}{m^3} U_{CoW} =$

	1	2	3	4	5	6	7
1	0.64	0.67	0.73	0.85	1.08	1.54	2.48
2	0.43	0.46	0.52	0.65	0.89	1.37	2.33
3	0.39	0.43	0.49	0.62	0.87	1.38	2.39
4	0.41	0.45	0.51	0.65	0.92	1.46	2.55
5	0.47	0.5	0.58	0.72	1.02	1.61	2.78
6	0.55	0.59	0.67	0.83	1.15	1.8	3.09
7	0.65	0.7	0.78	0.96	1.32	2.03	3.45
8	0.78	0.83	0.93	1.12	1.52	2.3	3.88
9	0.92	0.98	1.09	1.31	1.74	2.62	4.37
10	1.09	1.15	1.27	1.52	2	2.97	4.92

Results of Global Desalination Water Model

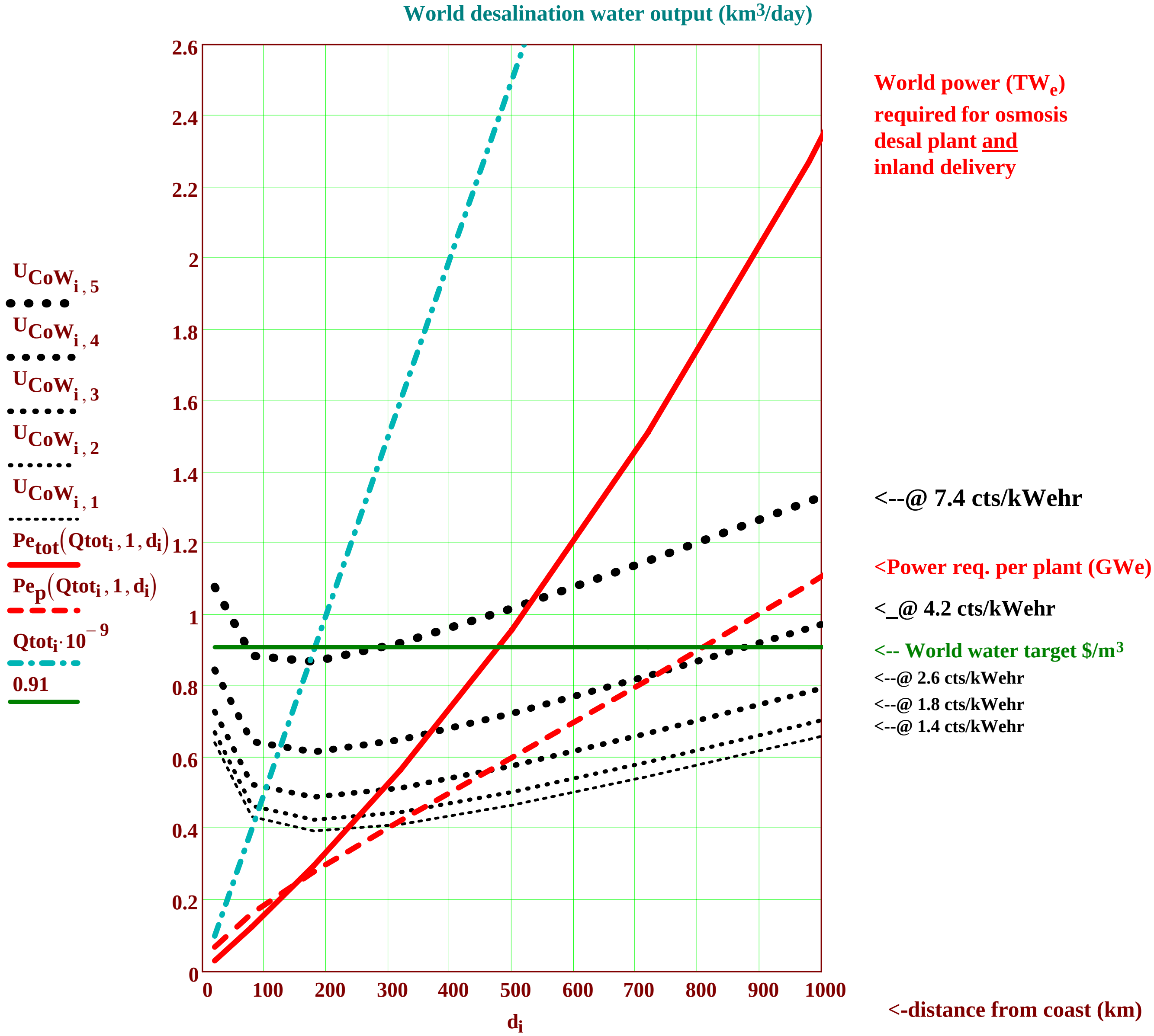

Figure 2: Unit cost of water UCoW ($/m^3) by ocean desalination vs distance d (km) from coastal plants for various costs-of-electricity CoE (black dotted lines). Also plotted is world total desalinated water output (in km^3/day)(dash-dot aqua line) along with total associated electric power P_{etot} in TW_e (solid red line), and associated individual desalination plant power P_{ep} in GW_e (dashed red line). The unit cost of water (0.91 $/m^3-see Table 1) that would require 7% of world GDP @ 10 km^3/day total output to produce by desalination is shown by the horizontal green line.

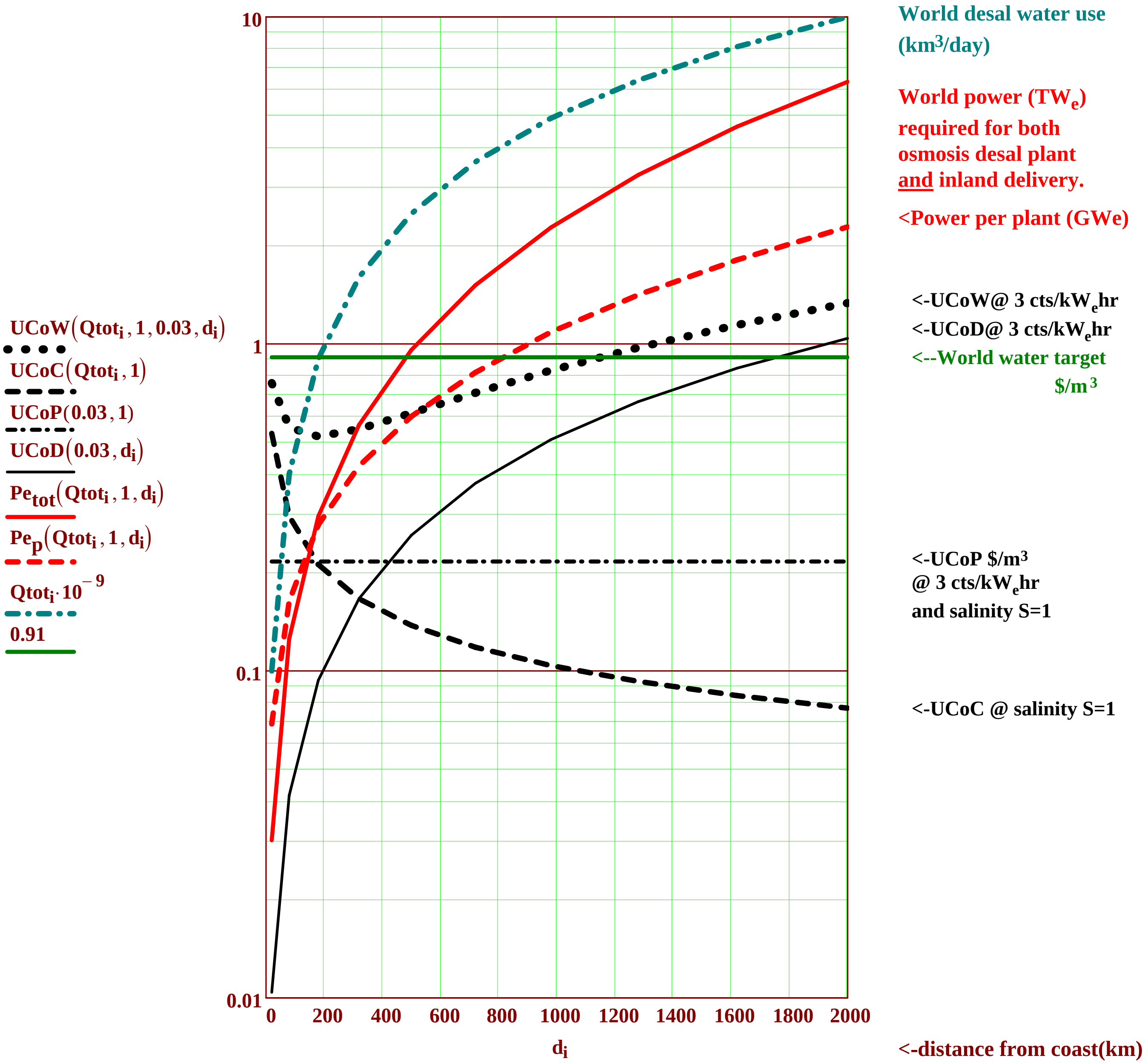

Figure 3: Unit cost of water UCoW ($/m^3) (black dotted line) and its component costs of capital UCoC (black dashed line), pumping UCoP (black dash-dot line), and delivery UCoD (black solid line) for ocean desalination vs distance d (km) from coastal plants for 3 cts/kWehr cost-of-electricity. Also plotted is world total desalinated water usage (in km^3/day) (dash-dot aqua line) along with total associated electric power P_{etot} in TW_e (solid red line), and associated individual desalination plant electric power in GWe (red dashed line). The unit cost of water (0.91 $/m^3-see Table 1) that would require 7% of world GDP at 10 km^3/day total output by desalination is shown by the horizontal green line.

Could Ocean Desalination be powered with biomass derived energy?

If one considers running osmosis plant and delivery pumps with bio-fueled-diesel engines @ 40% shaft-work efficiency instead of with electric motors @ 95% shaft efficiency, then ocean desalination would consume 120 MJ of bio-fuel energy per /m^3 of desalinated water [65 MJ for osmosis + 55 MJ for average world wide inland delivery]. However, we know that metabolic energy for life requires 2500 food calories/day/person = 10 MJ per person per day. From data in Table 1, the world currently consumes an average ~1m^3 of water/day/person just for irrigation for food, so irrigation water supports 10 MJ/m^3 of human metabolic energy required for life in feeding the world's population today . Some areas grow food only with natural rainfall-other areas grow food only with irrigation water. Only irrigation water is being counted here to supplement rainfall on the average worldwide: total water for agriculture including rainfall is several times more, but nonetheless irrigation water is an essential supplement for sustaining the world's population. Assume irrigation water as a percentage of total water needed for plant growth would be the same to grow more biomass for fuel energy in addition to food, even though total average rainfall is constant (an optimistic assumption given large amounts of land useful for biomass implied for 13 billion people). Now, if we assume current research in genetically-engineered superbugs could be developed to produce 10 X more bio-fuel energy per unit of agricultural biomass and water than humans process in metabolizing their food, then we might get 10 x 10 MJ/m^3 = 100 MJ/m^3 of biomass fuel energy per m^3 of irrigation water, still not quite enough to provide the desalination energy for the additonal irrigation water consumed by the biomass itself. ***Ocean desalination cannot likely be sustained with bio-energy alone.***

Discussion of energy options for global ocean desalination needs.

There are only a few electricity options with potential resource scale to meet the 3 to 6 (say, 5) Terawatts additional electric power needed to double the world's supply of fresh water by ocean desalination, but all options have difficult and different development issues that need to be resolved through further research: wind turbines, solar-electric, coal with CO_2 sequestration, fission with fuel breeding and re-processing, and fusion. Without attempting to list all development issues for all options, a few major ones are highlighted below in the form of critical questions for each option:

Wind: Expanding world wind power from current 75 GWe peak (15 GWe average) by 300 times, to 5000 GWe average for ocean desalination, would force wind turbines to be proliferated into more remote, less ideal wind locations. Desalination plant capital costs (Fig. 3) increase with intermittent use as (ave capacity factors ~0.2) $^{-1}$ ~ 5 X. Can wind power cost <3 cts/kWehr in such less ideal world average locations?

Solar electric: Solar photovoltaic power (integrated installed systems) have dropped steadily down to around 45 cents/kWehr average for current world total PV capacity ~4 GWe in locations averaging 20% solar irradiance. ***Can solar electricity drop another factor of 10 without hitting fundamental limits set by cost of materials (e.g. cost of silicon and durable platform materials)?***

Coal: There is enough coal for centuries, ***but not in every country*****, and while dirty coal plants, like the ones built every week in China, can meet the 3 cts/kWehr cost target,** ***what is the CoE from coal with CO2 sequestration?*** **CO_2 sequestration costs are really not yet proven, especially given the gargantuan amounts for coal-powered ocean desalination may not all sequester stably into conveniently-located reserviors.**

Fission: Growing from 300 to 5000 nuclear plants worldwide would force a large non-equilibrium shortage in startup fuel. Whether one considers high-conversion ratio Gen4 reactors or full breeders with reprocessing, the already soaring uranium ore prices begs the question: ***can sufficient startup fuel be obtainable at affordable prices for such huge growth rates in fission reactors, and with CoE<3 cts/kWehr?***

Fusion: After fusion ignition in NIF 2012 and in ITER 2020 is proven, ***can solutions be found to the first wall fusion neutron damage lifetime problem*****, and related to that, how soon could candiate materials be developed and adequately proof tested? Could the need for such materials be avoided? Fusion power system studies show CoE generally higher than for fission reactors, e.g., typically above 6 cts/kWehr.** ***How might fusion CoE be reduced below 3 cts/kWehr?***

The cost and difficulty of research to resolve all the above issues for all options might appear to be challenging, but in reflection, these challenges pale compared to the looming water crisis to sustain 13 billion people on a hot planet. The richest country in the world spends less than 0.1 % of its GDP on all forms of energy R&D, far less than typical insurance percentage rates. ***This can and must be changed.***