

GEOGRAPHICAL VARIATION IN PERFORMANCE OF AN UNGLAZED SOLAR SYSTEM MEETING WATER HEATING AND SPACE CONDITIONING LOADS

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ABSTRACT

This paper presents simulated performance across the U.S. of an unglazed collector system supplying domestic hot water, space heating, and space cooling loads. The collector model is based upon an ISO test for unglazed collectors that explicitly includes effects of wind and sky infrared. To provide realistic loads as location varies, building envelope characteristics vary according to code specifications. Maps of savings for heating and cooling are presented, showing a complex convolution of solar incidence and building load. The U.S. southwest region shows largest savings for both heating and cooling. Average heating efficiency varies from 13 to 28% for collector sizes from 24 to 6 m², respectively. Monetary savings and system cost goals are given for an all-electric and a (natural gas + electric) scenario.

1. INTRODUCTION

The "triple play" system here is intended to meet domestic hot water (DHW), space heating (HTG), and space cooling (CLG) loads. Solar-driven residential HTG and CLG present significant challenges over and above those for solar DHW. Most fundamentally, HTG is needed in winter when solar radiation is lowest. Furthermore, unless the roof has high pitch, low winter sun elevation angles lead to lowered incidence for collectors flat on the roof, or to unsightly rack-mounting. Also, HTG is a "part-time" load, becoming smaller in magnitude (with less cost savings potential) and shorter in time duration as the building envelope is thermally improved. Collector utilization improves if summer CLG is done with a thermally-driven system. However, such devices are costly and operate at higher temperatures where flat plate collectors are generally inefficient. In the U.S., glazed solar systems are almost never used for either HTG or CLG loads.

Interest exists in unglazed systems (1,2) because: i) unglazed collectors have potential for lower cost/benefit and improved aesthetics vs. glazed systems; and ii) unglazed PV-thermal hybrid collectors may work well together and are more aesthetic than separate systems. Collector cost could approach that of polymer pool collectors, at under \$1/ft² FOB, versus ~ \$15/ft² for glazed collectors. Unglazed collectors could be molded to "look like" an ordinary roof, similar in spirit to the "invisible collector" in (3). In new construction with a roof-integrated system, net system cost would be aided by credits for eliminating some of the regular roofing.

Along with all these advantages for unglazed collectors comes diminished and more uncertain heating performance, as compared to glazed collectors. Good performance data are key inputs to economic and market assessments. Convective coefficients are ~ 2-5 times larger than for glazed collectors, and are much more sensitive to the local wind speed. Efficiency decreases rapidly with increasing temperature difference, and temperatures are lower than for glazed systems. It is not clear *a priori* what cooling can be achieved in various climates, given the presence of both radiative and convective heat rejection mechanisms. To begin resolving these uncertainties, defining the most favorable markets, and setting system cost goals, this paper presents our first results of simulating an unglazed system meeting code-minimum-house loads across the U.S. After presenting the solar system and house modeling, variations across the country are presented. Maps of heating and cooling savings are presented, applying over range of collector areas from 6 to 24 m². The former is a realistic minimum for a DHW only system, and the latter a reasonable upper limit for a PV-thermal collector. These results enable the calculation of monetary savings and cost goals. Lastly, conclusions and future work are detailed.

2. MODEL DESCRIPTION

The solar system configuration assumed here is shown in Fig. 1. The solar system includes an unglazed collector array, hot and cold storage tanks, and controls with liquid-to-air heat exchangers for distribution. The model is implemented in TRNSYS (4). The modeling is briefly described in this section, with more detail given in (2).

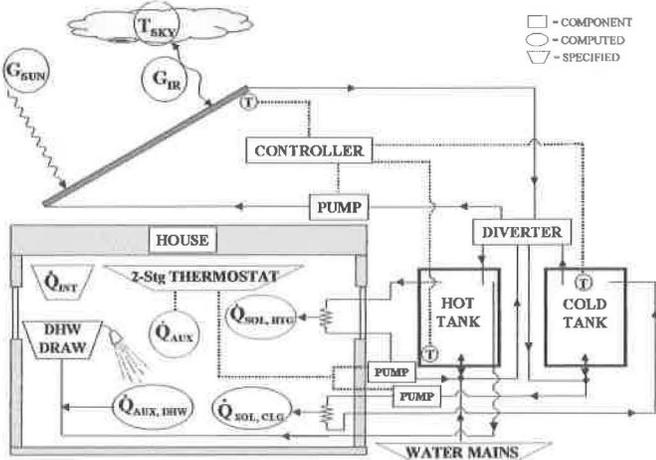


Fig. 1: Schematic model of unglazed system.

The unglazed collector model is described in (5,6). The collector performance can be expressed as:

$$\eta_{col} = F_r(\tau\alpha)_n K(\theta) - F_r U_l (T_{in} - T_{amb}) / G_{net} \quad (1)$$

G_{net} includes both short-wave solar and net sky infrared radiation between sky and a blackbody at ambient temperature. $F_r U_l$ and $F_r(\tau\alpha)_n$ are modeled as linear in v_{wind} :

$$F_r(\tau\alpha)_n = a_0 - a_1 v_{wind}, \text{ and } F_r U_l = b_0 + b_1 v_{wind} \quad (2)$$

v_{wind} is the wind 20 cm above the collector midpoint (6). We assume here that $(v_{wind}/v_{wind,TMY}) = 0.3$, with sensitivity to this ill-determined factor shown in (2). Further work is needed to provide guidance on this input. a_i, b_i data are taken from (6) for the collector labeled 'FA357.' Collectors are run at the tested flow rate. Lower flow rates (as with thermosiphoning systems) will reduce performance.

The solar system key parameters are given in Table 1. The freeze protection approach is left unspecified. Parasitic power is ignored, so savings are to be interpreted as maximum possible. Five nodes are used in the tanks, giving moderate stratification. The storage tanks are linked to the house through fan-coils. A heat exchanger between storage and DHW that would be required by code is ignored here. CLG coil latent loads are accounted for. A multi-stage

thermostat stages the solar loop first followed by auxiliary if solar cannot meet the load, with setpoints in Table 1.

TABLE 1: KEY MODEL PARAMETERS

Parameter	Value	Units
House model:		
Floor area; window area	186; 33	m ²
Infiltration rate	0.57	ACH
DHW T _{set}	55	°C
DHW draw	242	liters/day
Solar HTG; CLG T _{set}	21.1; 23.9	°C
Aux. HTG; CLG T _{set}	20.0; 25.6	°C
Daily internal gains	32.5	kWh/day
Solar system model:		
Collector a ₀ ; a ₁	.88; .029	-; s/m
Collector b ₀ ; b ₁	10.24; 4.69	W/m ² °C; Ws/m ³ °C
Collector slope	30	Degrees
Panel area	2.92	m ²
Flow rate/A _{col}	248	kg/hr-m ²
HTG - ΔT _{on} ; ΔT _{off}	5.56; .1	°C
CLG - ΔT _{on} ; ΔT _{off}	-2.0; -0.1	°C
Tank storage/A _{col}	80	kg/m ² -coil
Tank U Value (R)	1.14 (R5)	W/m ² -°C
HVAC pump (max)	800	kg/hr
ε _{HTG-coil} ; ε _{CLG coil}	60; 62	%

The house is a one-story, slab-on-grade, single-zone model, intended to be simple whilst providing realistic loads. The moisture balance and moisture capacitance models in (4) are activated. Key invariant parameters are shown in Table 1. Except as noted below, other key house parameters vary with site heating degree days (HDD), as specified in (7) for the code compliance reference house (systems analysis path). In (4), window properties are derived from WINDOW5 (8), with an extensive library of realistic coatings, gas fills, frames and glazings. For HDD > 3500, we were not able to create windows with both the specified solar heat gain coefficient (SHGC > .68) and the specified U value. Rather than defining fictitious coatings, we chose to achieve the specified U-values, using the *highest attainable* SHGC, as shown in Table 2. Other exceptions to (7) include: i) overhangs added on windows on S/E/W, to realistically lower cooling loads; ii) constant air change rate at 0.57 ACH; and iii) internal gains and $T_{mains}(t)$ are computed as in (9). $T_{mains}(t)$ is set to a constant ($T_{mains,avg}$) plus sinusoid. $T_{mains,avg}$ is set to site $T_{amb,avg} + 6$ °F, with amplitude ~1/2 the ambient temperature annual amplitude. HTG and CLG auxiliary are not modeled in detail. HTG, CLG data presented below are energy to zone; these values must be divided by equipment conversion efficiency to obtain auxiliary fuel usage.

TABLE 2. WINDOW PROPERTIES VS HDD

HDD [°F-days]	U_{glaz} [W/m ² -C]	SHGC [-]
≥13,000	1.38	0.46
9,000 – 12,999	1.455	0.502
6,500 – 8,999	1.602	0.533
4,500 – 6,499	1.697	0.534
3,500-4,499	2.174	0.594
2,600 – 3,499	2.524	0.367
700 – 2,599	2.637	0.372
< 700	4.04	0.386

3. PERFORMANCE RESULTS

Simulations were done at all TMY2 sites (10), for collector areas of 6, 12, and 24 m². Normalized, unit-area savings (for maps) are given in units of GJ/m²-yr, denoted as q_{sav} . The average and maximum q_{sav} for each end use are shown in Table 3. Note that 1 GJ ~ 10⁶ Btu. The geographical variation between minimum and maximum is nearly identical for the three areas, so a single map can be used to display geographical variations for all collector sizes. Figs. 2 and 3 are maps for $q_{sav,HT}$ and $q_{sav,CLG}$, respectively. The map legends show three columns of numbers besides the color scale, each labeled with a collector area, that associate scale colors with unit area savings. Contours should not be taken too literally, as the database of 238 sites is far too sparse to draw contours with meaningful details. The TMY2 database lacks small-scale data (e.g., no sites in the Sierra Nevada), leading to sometimes misleading contours. Nonetheless, contours reliably represent general trends across the country.

The $q_{sav,HT}$ map correlates well with solar incidence, as expected, but it also reflects loads. $q_{sav,HT}$ in FL are low because loads are low, which caps savings and drives the system more toward stagnation. $q_{sav,HT}$ are low in the northeast because of lower incidence and lower ambient temperature (which lowers unglazed collector efficiency). The region with largest $q_{sav,HT}$ is the U.S. southwest, peaking near the CO-NM border and extending westward. A second favorable area appears in the southeast, peaking in SC. In these favorable areas, sun is good to excellent, the DHW is relatively large, and the winter, though not severe, has significant HTG loads. Cooling savings are significantly smaller than heating savings. Averaging over all sites, $q_{sav,CLG,avg}/q_{sav,HT,avg} \approx 1/4$, independent of collector size. Areas showing the largest $q_{sav,CLG}$ are: i) the arid, mild southwest, peaking in central-south NM/AZ and extending into NV/central CA; and ii) Florida. $q_{sav,CLG}$ is also large for HI and Puerto Rico, although residential cooling is rare in these areas.

TABLE 3. UNIT-AREA SAVINGS¹⁾, AVG. and MAX.

End Use \ A _{col}	6 m ²	12 m ²	24 m ²
$q_{sav,DHW,avg}$	0.98	0.59	0.34
$q_{sav,HTG,avg}$	0.56	0.50	0.40
$q_{sav,CLG,avg}$	0.36	0.28	0.20
$q_{sav,DHW,max}$	1.28	0.74	0.43
$q_{sav,HTG,max}$	1.69	1.25	1.04
$q_{sav,CLG,max}$	1.23	1.05	0.81

1) Savings are given in units of GJ/m²-yr.

Absolute magnitude of savings and loads (denoted as Q_{sav} , Q_{load}) are displayed vs. heating degree days in Figs. 4,5 for heating and cooling, respectively. Trend changes in $Q_{load,HTG}$ at HDD ≈ 3500 in Fig 4 are due mainly to a change of the SHGC of windows, from ~.37 to ~.59 at that point. This results in a step change in the building’s passive solar gains, lowering the HTG load. Dips in the load trend line are at sites with higher solar incidence. At a given A_{col}, there is significant variation in $Q_{sav,HT}$ for similar HDD values, with range of a factor of ~2. This is probably a reflection of the ~factor-of-2 variations in solar incidence. Sites highest in savings are mostly western sites (CO, NM, AZ, NV, WY) with higher solar incidence and high loads. The ordering of savings amongst sites is preserved as area changes.

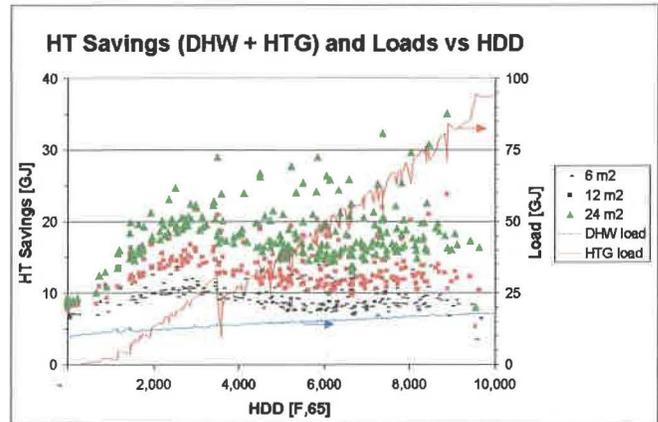


Fig. 4. Heating Savings and Loads vs. HDD (< 10,000 °F-days). Symbols are heating efficiency (Eq. 3). The solid lines are DHW and HTG loads (right axis).

$Q_{sav,CLG}$ and $Q_{load,CLG}$ vs. HDD are shown in Fig. 5. $Q_{sav,CLG}$ correlates with decreasing $Q_{load,CLG}$, for HDD above about 4000 °F-days. Higher points above the trend line between ~1000 - 4000 °F-days are dominantly dry western climates with hot summers, indicating perhaps the increased radiative cooling and cooler night-time temperatures at these sites. For humid sites, radiative cooling is low and cooling is almost entirely convective. In hot/humid sites like Miami, most cooling is during the milder swing seasons (2).

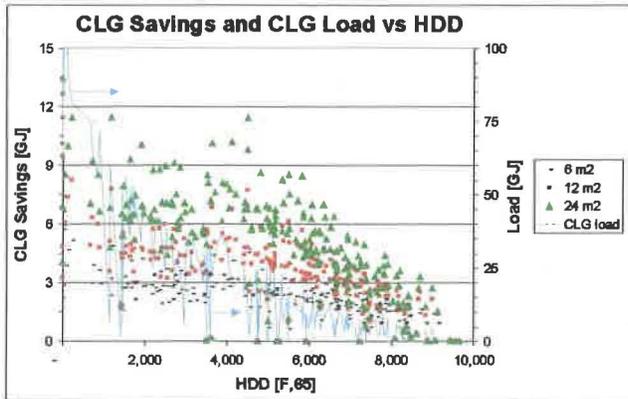


Fig. 5. Cooling savings and load vs. HDD (< 10,000 °F-days). The symbols are $Q_{sav,CLG}$ (left y axis) for the 3 sizes. House cooling load (right axis) is the solid line.

Lastly, it is useful to look at results in terms of efficiency. A heating efficiency η_{HT} can be defined as:

$$\eta_{HT} = \frac{\text{total savings}}{\text{total incidence on collector}} = \frac{(Q_{sav,DHW} + Q_{sav,HTG})}{(A_{col}H_{sun})} \quad (3)$$

Fig. 6 shows η_{HT} vs. HDD, for the 3 collector sizes. Variations in η_{HT} are reduced vs. variation in $Q_{sav,HT}$, as generally true for solar systems. η_{HT} increases ~linearly with HDD in region $0 < HDD < 3000$ °F-days, as the HTG load initiates and DHW load increases. Above 3500 °F-days, η_{HT} is relatively constant. Averaging over all sites with $HDD > 3000$ °F-days, η_{HT} is 25%, 18%, and 13% for 6, 12, and 24 m² collector size, respectively. Note at the small size, this efficiency is ~60% of the efficiency of a small glazed SDHW system (11). With constant load, η_{HT} is a decreasing function of size, as holds for solar thermal systems generally. η_{HT} decreases by a factor of ~2 as area increases a factor of 4. Conversely, $Q_{sav,HT}$ increases a factor of 2 when area increases a factor of 4. Diminishing return with increasing area is evident.

4. COST SAVINGS AND SYSTEM COST GOALS

Cost savings depend significantly on whether natural gas is used, because gas is ~1/3 the cost of electric heat. An electric heat pump might be preferred in all electric case, but we assume purely resistance heat, providing an upper limit of cost savings. We assume electricity at 10 ¢/kWh, natural gas at 80 ¢/therm (one therm = 10⁵ BTU), annual efficiency for gas of 70%, and chiller COP of 3. In the U.S. southwest, natural gas penetration is high, and one would use the lower gas \$ savings generally. In the southeast, natural gas penetration is low, and we would generally use the higher electric only savings.

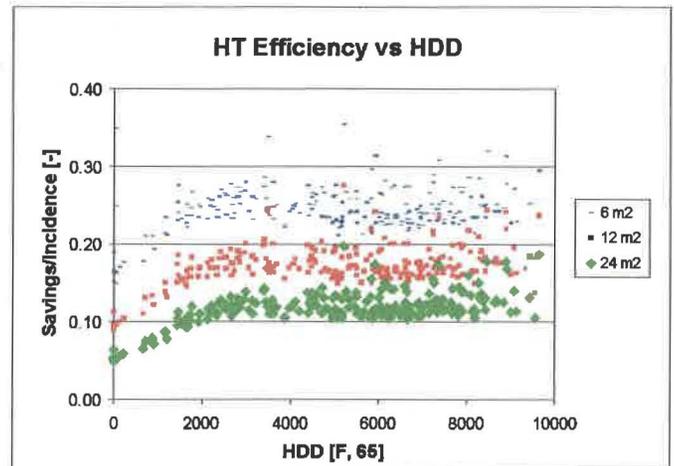


Fig. 6. Heating efficiency η_{HT} versus heating degree days HDD (< 10,000 °F-days). η_{HT} is defined in Eqn. (3).

Fig. 7 shows unit area monetary savings across the U.S. As in energy savings maps, for each collector area the maps were nearly identical as long as min/max values were adjusted accordingly. Surprisingly, the maps don't change much in all-electric vs. with natural gas either, although the electric savings contours do shift slightly northward, reflecting the additional weighting on heating. Fig. 7 thus has six columns of values, for 3 areas at 2 fuel splits. Not surprisingly, the monetary savings map mimics the energy savings map. Highest savings are in the southwest, with a second peak in SC and westward.

Goals for total system cost (hardware, installation, marketing, and present value of future O&M) can be set based upon a desired simple payback period (SP). SP is (system total cost)/(annual savings). A functionally-related metric is return on investment (ROI). Note that $ROI \approx 1/SP$. At SP=10 years, ROI is ~10%. These values are taken here as a reasonable acceptable maximum for SP/minimum for ROI. With this assumption, the cost goal is calculated simply as 10 times the annual savings. For Fig 7 with natural gas, cost goals vary geographically from \$100/m² to \$230/m². Cost goals are lowest (most difficult to attain) where performance is lowest. These costs goals should be compared to the cost of today's solar water heating systems of about \$600/m². The cost goals will be difficult to attain without low-cost collectors and storage. Against electricity only, savings are about 2.3 time higher, and cost goals similarly inflate by the same factor, ranging from ~\$230/m² to ~\$530/m². The all electric goals are more forgiving. For new construction and roof-integrated systems, there can be roof-replacement credits estimated of order ~\$50/m² which would help reach the goals.

5. CONCLUSIONS AND FUTURE WORK

DHW, HTG, and CLG savings were computed for an unglazed solar system at all TMY2 locations, for collector areas of 6, 12, and 24 m². Savings are considered as upper limits attainable, since parasitics were ignored and other assumptions made to elicit maximum performance. Over all sites and systems, heat savings averaged about 1 GJ/m², with cooling savings about 1/4 as much. Savings for both heating and cooling were highest in the U.S. southwest, peaking in central/northern NM and staying large westward through the CA central valley.

Savings were calculated. Annual savings ranged from ~\$10/m² to ~\$23/m² (~\$23/m² to ~\$53/m²) for all-electric (electric + natural gas) scenario. Cost goals can be set at 10 times the annual savings. The cost goals for natural gas appear unattainable with today's system costs.

6. NOMENCLATURE

Symbols:

a_i, b_i	Collector model coefficients from test
F	Heat removal factor
G	Radiation
HDD	Heating degree days, base 65
K	Incidence angle modifier
Q	Energy
R	R value of tank insulation (English units)
SHGC	Solar heat gain coefficient
T	Temperature
U	U value
η	Efficiency
θ	Incidence angle
$\tau\alpha$	Transmission-absorption product

Subscripts:

amb	Ambient temperature
avg	Average over all TMY2 sites
CLG	Space cooling
col	Collector
DHW	Domestic hot water
elec	Electric auxiliary
gas	Natural gas auxiliary
HT	Heat, combined DHW and HTG
HTG	Space heating
in	Inlet temperature of fluid
l	Loss
n	Normal incidence
net	Net radiation (short λ – long λ)
r	Heat removal
sav	Savings or saved
sun	Solar incidence
wind	Wind

7. ACKNOWLEDGMENTS

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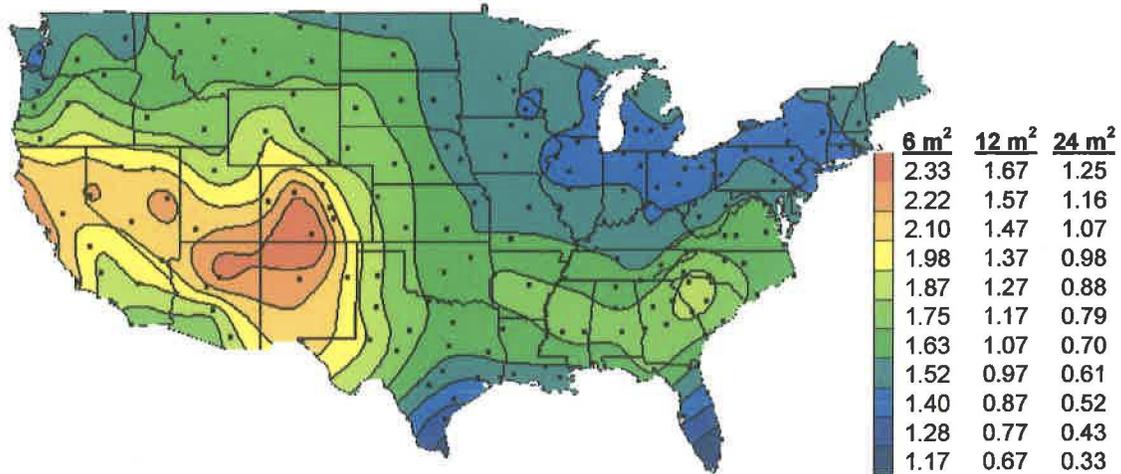


Fig. 2: Unglazed system space heating + DHW savings (legend = GJ/m²-yr), for three collector areas.

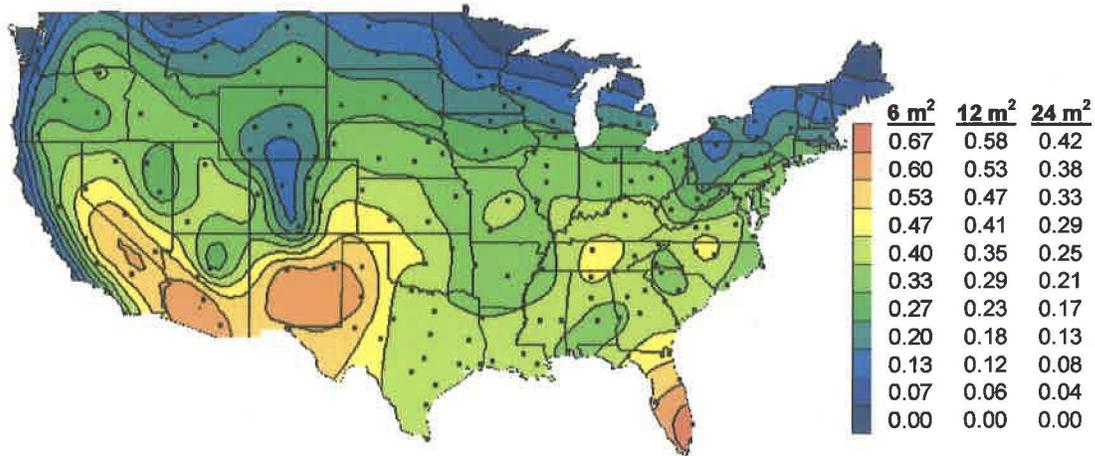


Fig. 3: Unglazed system space cooling savings (legend = GJ/m²-yr), for three collector areas.

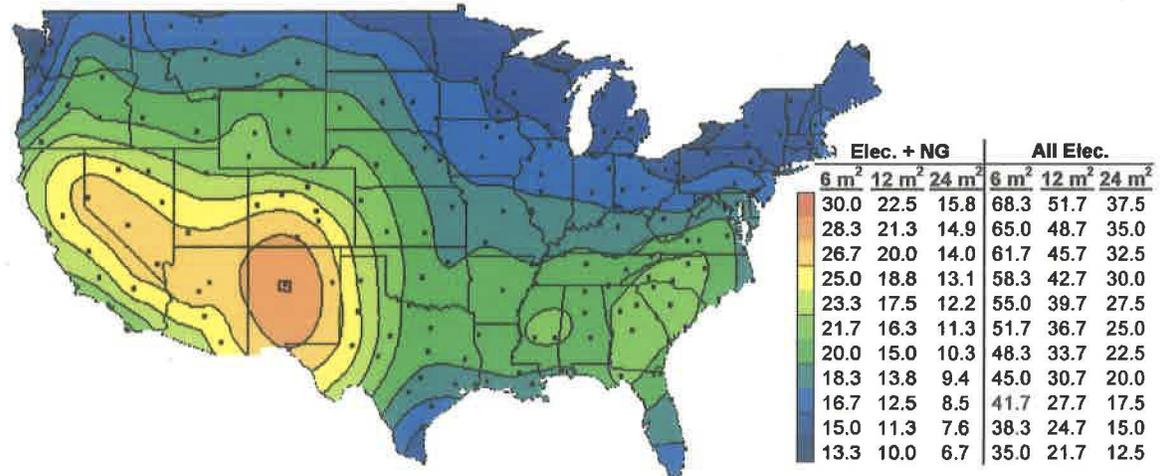


Fig. 8. Total monetary savings/year (legend = \$sav/m²-yr), for three collector areas and two fuel scenarios (electric + natural gas, and all electric). Unit area cost goals for 10 yr simple payback are 10 times the unit area savings.