Energy Use and Yields in Tomato Production: Field, High Tunnel and Greenhouse Compared for the Northern Tier of the USA (Upstate New York)

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Introduction

The impending probable shortage of liquid fuels has alerted policy makers and the public that we need to account for the energy needs of agricultural production and the energy costs of bringing food to our tables. It is for these reasons that energy budgets and types of energy used in food production are of great interest.

In the following, the energy use being compared is only that part supplied by humans at a cost. The energy accounted for is that delivered as electricity and various fossil fuels used for crop production (called "direct energy"), and that required to manufacture building materials, tillage equipment, and supplies such as fertilizer and pesticides (called "embodied energy"). The energy to extract fossil fuels and generate electricity is also taken into account; it can be considered to be embodied energy. It requires money to acquire and manipulate the energy we are accounting for, and its use results in carbon dioxide and other greenhouse gas emissions.

Materials and Methods

The estimates for energy use in field and greenhouse production of tomatoes and their transportation, and associated carbon dioxide emission, are taken from an extensive study of production and transportation energy use to import selected fruit and vegetable crops to New York, as compared to growing them locally. The study was commissioned by the New York State Energy Research and Development Authority (NYSERDA) and executed by the authors Albright and de Villiers. Much more extensive data, analysis, and references than are presented in this article be can be found in the NYSERDA report which is available at the NYSERDA web site, under the title "Energy investments and CO_2 emissions for fresh produce imported into New York state compared to the same crops grown locally" (NYSERDA, 2009). The file can be accessed at http://www.nyserda.org/publications/locally%20grown%20imported%20produce.pdf

Greenhouse energy use was computed *de novo* in the NYSERDA report, for a hypothetical state-of-the-art greenhouse with one ha of growing area with an attached 0.2 ha head house, and is detailed and comprehensive, covering a number of different production scenarios. Estimates for field energy use are taken from the NYSERDA report, where they were composed from a number of sources, including Stanhill's (1980) paper on energy use in several different tomato production systems and Pimentel's *Handbook of Energy Use in Agriculture* (1980). These early estimates have been reviewed and adjusted where necessary to reflect changes in practice. Energy use in high tunnel tomato production was generated *de novo* for this article using field data on yields and input requirements compiled by author Reid, *vis a vis* practices of a successful local high tunnel grower. Estimates of energy use in transportation were based on Mudge (1982), adjusted for present-day conditions. Historic tomato production data in the NYSERDA report were taken from several federal and state government agencies concerned with agriculture, particularly the National Agricultural Statistics Service (NASS) and USDA Economic

Research Service (ERS), and cross checked for consistency. In deciding yield figures, the aim was to determine an average net useable yield (as opposed to gross yield) appropriate to the energy estimates for the idealized production scenario. In the case of greenhouse tomato yield, the figure of 68.4 kg/m^2/yr (14 lbs/ft^2/yr) for 10-month cropping with CO_2 enrichment from the NYSERDA report may be compared to the average yield for Canadian greenhouse industry as a whole of 49.4 kg/m^2/yr, or 10 lb/ ft^2/yr, given by Calvin and Cook (2005). As in all national/regional yield figures, the average mixes a variety of cropping practices and durations of cropping, whereas we have in mind a specific production method and cropping duration.

We have estimated direct energy use in glasshouse tomato production using climatic data for upstate New York, an area in the northern tier of the USA at latitude +43 degrees, subject to cold winters and poor winter light. It can be considered a worst case scenario for the greenhouse tomato industry in the northeast USA.

We have used an estimate for a 10-month period of greenhouse production in Upstate New York, with CO_2 supplementation, but without light. A 10-month production period in which CO_2 supplementation is used closely reflects current practice in the northern part of the USA and can be considered applicable for the eastern Canadian tomato industry as well. The following section is excerpted from the research report to NYSERDA (2009).

"Tomato greenhouse production practices are constantly evolving, and several different systems are in use at this time. Scheduling of the annual crop cycle is quite different in different parts of the country, with down-time scheduled for midsummer in the south and mid winter in the north. However, in the northern temperate regions there is economic pressure to extend the harvest period as much into the winter as possible. As the account following will show, tomato production is a highly specialized practice.

In large, state of the art, greenhouses in the northern tier, such as those at Leamington Ontario, the largest complex in North America, it is typical to start seedlings in small rockwool blocks (e.g. in December) in a dedicated part of the facility about 8 weeks in advance of when they will be set out in the greenhouse on large rockwool slabs (e.g. in February). The slabs on which the seedlings are placed rest in gutters/troughs that are raised some 2 ft (0.6m) above the floor. Each plant is supplied with a drip-irrigation loop, through which it is irrigated many times a day. Excess nutrient solution (c. 20%) is drained via the trough to a collection tank, where it is periodically treated, amended, and recycled.

In greenhouse tomato production, the same plants are kept producing as long as 12 months before being replaced, and they become very tall. Plant spacing is important for getting light down to lower leaves. Plants are arranged in long double rows. The double rows are just over 5 ft (1.6m) apart, center to center. The distance between paired plants in the double rows themselves is approximately 2ft 3in (0.69m) apart, leaving 3 ft (0.91m) clear between outer rows for harvest and plant tending operations. Motorized vehicles run on tracks in this 3 ft (1 m) alley. Plants typically are 18 in (0.5m) apart within the row.

Before new plants are so tall they will fall over, they are strung up to an overhead wire/cable about 10 ft (3m) above the floor. Additional turns are taken about the stem of each plant to support new growth every week. Plants are pruned to just one stem by pinching out other shoots than the apical meristem. The number of fruits allowed to develop in each flower truss is also limited, typically to 4 for large tomatoes. Bumble bees are used to pollinate plants or, alternatively, flowers trusses are vibrated to ensure self *pollination. As fruits get heavy, each fruit truss may be individually supported to prevent breakage, depending on cultivar and type of tomato. When plants have reached the desired final height (c. 8ft or 2.5m from the base), they are "let down" approximately 16 inches (40cm) as frequently as they grow back to the final height (which is dependent on weather conditions and fruit load, but might be every week). In this process, lower leaves are stripped and the bottom part of the stem is made to lie horizontally at the level of the rockwool substrate, in the same direction for all plants. In time, a thick horizontal cable of tomato stems is formed, and the vertical productive part of the plant may end up 25 feet or more away from its starting point and root system. Fruit is harvested about twice a week at breaker stage, or a more mature stage; frequency of harvest and maturity stage depend on growing conditions and market requirements.*

In the primary scheme we are positing, the crop is grown in this fashion for 10 months, during 8 of which fruit is harvested (April to November), after which it is terminated, and the greenhouse cleaned and sterilized. For two of the coldest and darkest months the greenhouse is unoccupied (December and January). However, during this time seedlings are under production elsewhere in growth chambers or a small lighted greenhouse to be ready for transplant in February. Often seedlings are bought in from greenhouse operations specializing in seedling production."

The high tunnel production system envisaged spans a period of 6 months, with seeds sown in March, transplanted in April, and harvesting beginning in mid-June, and lasting until early November. The plants are grown in the ground, fertilized through the trickle irrigation system, and trellised in a manner similar to the greenhouse example. Use of natural enemies for insect pest control, and maintaining good ventilation obviates the need for significant pesticide applications in this case.

Field producers limit their production to the locally effective growing season, so the normalized energy estimates for these production systems are reasonably representative of many other areas of the country. To provide a comprehensive picture of energy needs of tomato field production, we have provided summaries for three systems: a field production scheme for New York, which is based on that employed in Florida in the winter; and staked and unstaked systems for field tomato grown in California. We take the staked field tomato crop grown in California to be representative of Mexico. The principal differences among these systems are the need for mulching, fumigation and frequent fungicide applications in the humid Northeast and Florida, and the need for trellis materials for the two staked systems,

In presenting results we have distinguished two main categories of energy use, embodied energy use, referring to energy expended in manufacture of things, and direct energy use, referring to consumption of fuels and electricity during production. We have attempted to separate embodied energy use further into three categories: (1) that invested in the permanent structure, (2) that invested in equipment and fixtures of considerable permanence, and (3) that used in the manufacture and delivery of materials and supplies consumed during each crop cycle. In truth, these distinctions can be made only roughly, yet they may help assessment of energy use.

Results and Discussion

As shown in Table 1, winter greenhouse production of tomatoes in the northern tier of the country over a 10-month season requires use of an order of magnitude more energy per kilogram of product than production tailored to the summer season in field and high tunnel production. Carbon dioxide emissions are also correspondingly higher, and, as a general rule, so are costs for energy. The energy use for heating comprises over 90% of total energy use in this estimate. Clearly growing tomatoes in the North in winter incurs a very substantial heating bill. It would be substantially less in virtually any coastal or more southerly location in the USA or, alternatively, if the greenhouse production season was limited to those months when no heating was required, as, for instance, the high tunnel season of 5 to 6 months. (In the latter case, embodied energy per kg of product would rise somewhat, however, because much of embodied energy is independent of cropping duration and would be assigned to a smaller annual yield.)

Field and high tunnel producers may use a minimal amount of heating to protect seedlings from frost when first put out but, by and large, they use negligible energy for heating. High tunnels double the two-month productive season of the field crop in New York, without requiring the use of supplementary heating, and have this natural advantage over field production, even if cost of production per kilogram is a little higher. Generally, quality is superior as well, and the crop is less vulnerable to unusual weather or diseases such as early blight (*Alternaria solani*). High tunnels are able to supply a higher profit margin <u>per unit of product</u> than greenhouses, if greenhouse production is extended into winter months when heat must be paid for. (However, sales volume becomes an issue for high tunnels.) They are also superior to greenhouses <u>environmentally</u> if the greenhouses use fossil fuels for heating rather than renewable energy sources (such as woodchips, which would not introduce new carbon dioxide emissions, or electricity generated by wind, water or sun). Typically, present-day glasshouses use natural gas for heating, which entails introducing new carbon dioxide emissions into the atmosphere.

High tunnels have the distinct advantages over greenhouses in New York of lower production cost per unit of product, being more benign environmentally than greenhouses (as they are currently operated) in terms of carbon dioxide emissions, and potentially being very local indeed. They have the advantage over field producers of a higher quality product, greater reliability, and earlier entry into the summer produce market. On the other hand, high tunnels in Upstate New York only supply tomatoes for about a four-month period, which sets a limit on market penetration as well as gross profit potential. The public insists on tomatoes year round. The challenge for high tunnel producers is to be able to market their perishable product immediately when it becomes available, and not remain as seasonal farmers' market suppliers. It might be possible to secure a position in supermarket venues on a seasonal basis, forcing the rest of the tomato industry to adjust, if a reputation for predictability, high quality and low price could be built up over time, but it is a tall order while production is seasonally erratic, scattered geographically, and limited in volume. Who is to set standards and enact a master plan to expand the high-tunnel sector of agriculture, given the virtues of the production system?

At present, northern USA greenhouse tomato producers are in competition with Canadian greenhouse growers (located particularly in Leamington, Ontario; Papadopoulos and Gosselin, 2007) and greenhouse growers in the southwest of the USA (particularly Texas and Arizona). Even stronger competition comes from field and high-tunnel producers in Florida, California and Mexico. (Local high tunnel and field producers are so far a relatively minor factor.) Of the field producers, Florida dominates in the winter months, and Mexico and California the rest of the year. Thus, in terms of energy use and carbon dioxide emissions, the most important comparison for northern greenhouse producers is with remote growers, primarily field, who are able to grow tomatoes during winter months or year-round.

For some remote producers (Mexico, Arizona, California), transporting tomatoes uses up to three times the energy required for production and, at the present time, it is all in the form of diesel, a petroleum fossil fuel (See Table 1). In assessing greenhouse energy use and emissions, transportation energy needs to be considered in addition to production energy. Table 1 shows that the estimate for California production energy for field tomato is very similar to that for NY high tunnel tomato, which is as one might expect given the climatic advantages of California. Florida field tomato energy requirements are a little higher, in part because of a higher requirement for pesticides. When we take into account transportation energy as well as production energy (Table 1), the remote field producers still use considerably less energy than Northern greenhouse producers. However, economically and environmentally their future market position is vulnerable because transportation is based on petroleum fuels and the price of petroleum fuels in destined to rise.

If we compare the embodied energy use on a per kilogram product basis, there is no significant difference between greenhouse, high tunnel and field production regardless of location. The differences come when transportation energy and heating energy are taken into account. What can be said in defense of northern greenhouse production versus any remote production, is that there is currently only very limited reliance on petroleum during production, and that use of renewable energy sources exclusively is possible, and already planned in some facilities (MacArthur, R. 2009, personal communication). What petroleum use there is derives from its use for electricity; some 14% of New York State electricity is generated in oil-fired power stations (NYSERDA, 2007). Electricity is used to operate vent fans, shade curtains etc. For heating, greenhouses can exploit waste heat from other industrial enterprises, including landfills engaged in electricity generation, or convert from natural gas to carbon-neutral biofuels such as wood chips, if desired. The effectiveness of these measures depends on location. Electrical energy generated from wind, water, and the sun are also safe energy sources with near-zero net carbon emissions, feasible for greenhouse use. Field agriculture, on the other hand, depends on petroleum for operation of mobile equipment and transporting the product, and it is hard to envisage this reliance changing rapidly or radically.

The greenhouse tomato industry is alive and healthy along the border of Canada and the USA near large population centers. The challenge will be to keep up with societal/governmental demands for reduced carbon dioxide emissions while still remaining profitable -- through choice of locations with favorable energy costs and/or climatic advantages, by switching energy sources, and through technological improvements. Night curtains, for instance, have been shown to reduce winter heating needs by 25% to 65% depending on how sophisticated they are. Supplemental CO_2 can reduce supplemental lighting required for consistent year-round production by 50%.

Ninety five percent of tomatoes consumed in New York come from out of state (Peters et al, 2002). One can make the argument this is as it should be. There is a certain appeal to the idea of growing things where they grow best, which is natural to farmers and growers on a local level, who always pick the best location available for growing a crop. The idea can be applied by extension on a national level. However, our loyalties tend to be strongest for the places nearest to us, and there is the competing value of supporting the local economy over the state and the national economy. There is growing awareness of the environmental hazards of the high level of carbon dioxide emissions, which are currently very much a part of long-range agricultural distribution.

Production of fresh produce for out-of-season consumption on a scale to meet the needs of the northern population is currently only possible by shipment from places where the climate is suitable for winter production, and it is likely to stay this way during the immediate future. However, in certain crops, remote field producers in ideal growing regions such as California will increasingly have to compete with protected-culture practitioners located more closely to markets as transportation costs rise and the desire to decrease carbon emissions increases. All the perishable salad crops fall in this category, along with fresh tomato for table consumption. In order to retain distant markets, the challenge for remote producers is to motivate a revolution in transportation such that costs and emissions are substantially reduced. Where large urban centers are the destination, revival of the rail system will cut emissions by as much as 50%, without switching from diesel, and even without much improvement in technology. A start has been made in delivery of apples and other produce from the state of Washington to New York on a dedicated twice-weekly freight train and, so far, is counted a success. The energy estimate for moving apples from Washington to New York by railcar is 53% of that moving them by road (NYSERDA, 2009). A north-south line from Washington to California is planned, and a line from California to the Northeast. It is quite conceivable that, with advances in wind and solar energy production, the rail system could be electrified and powered by renewable energy sources distributed across the Great Plains.

Conclusions

All agriculture uses various degrees of environmental modification. Even in field production of tomato in Florida, trellises are supplied for support, and the soil is mulched and sub-irrigated. Here we have compared three production systems encompassing minimal to maximum environmental modification. The natural question is, “What is the return on the investment?”

In the comparison of three production systems there are very large differences in yield/unit area as a result of the environmental manipulations (Table 1). When field production is compared to high tunnel production in New York, the increase in yield overmatches the increase in energy inputs to such a degree that energy inputs per weight of product actually go down compared to field production in New York, and match energy inputs in California. The environmental modifications for greenhouse production bring about a spectacular increase in yield, over both field and high tunnel production, but in this case the energy inputs increase even more, resulting in a substantial increase in energy inputs per unit weight of product. If high tunnel tomatoes could be produced year-round, there would be no contest. But they cannot, whereas greenhouse tomatoes can, thereby securing market placement and a large market share over most of the year.

The main competitors for the Northern greenhouse tomato grower are remote producers in Florida, Mexico, and the southwestern USA (Cook, et al, 2005). These growers must contend with the cost of transportation to compete with greenhouse growers located in the Northeast. This cost is likely to increase at a faster rate than the cost of energy for heating greenhouses, which currently is achieved predominantly with natural gas, but can also be achieved using waste heat or solid fuels such as wood and coal. The type of energy resource used by remote growers is predominantly petroleum fuel, whether for operating tractors, tractor trailers, or trains. Not only is this likely to increase dramatically in price as world demand increases for a dwindling supply, but there is no ready substitute for it. Field growers supplying the Northeast will also have trouble reducing carbon emissions, should they come to be taken seriously. However, northern tomato growers, although they require more energy per unit weight in growing tomatoes, use no petroleum directly as fuel, and have numerous options for greatly reducing energy use and carbon emissions.

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Table 1. Energy Use in Production of Tomato under Three Cropping Systems in Upstate NY, and for Production and Transportation to NY by Remote Suppliers

	NY High Tunnel	NY Greenhouse	NY/Florida Field Crop[4] Staked	Ca, Mexico Field Crop Staked	Ca, Mexico Field Crop Bush[5]
Embodied energy use (MJ/kg)					
Permanent structure	2.00	1.52	0.00	0.00	0.00
Long-term equipment[1]	0.11	0.62	2.98	1.63	0.14
Subtotal: durable items	**2.12**	**2.14**	**2.98**	**1.63**	**0.14**
Consumables (Chemicals, Mulch, Seedlings etc.)[2]	0.78	0.96	2.51	0.55	1.04
Embodied Energy Total	**2.90**	**3.10**	**5.49**	**2.18**	**1.18**
Direct energy use (MJ/kg)					
Machinery energy[3]	0.10	2.02	1.59	0.95	2.19
Heating energy	0.00	60.86	0.00	0.00	0.00
Subtotal: fuels and electricity	**0.10**	**62.88**	**1.59**	**0.95**	**2.19**
Total Production Energy (MJ/kg)	**3.00**	**65.98**	**7.08**	**3.14**	**3.37**
			From Florida	From Ca	From Mexico
Trucking Energy to NY (MJ/kg)	**0.4**	**0.4**	**3.8**	**10.7**	**9.3**
Production+Trucking Energy Use[6]	**3.4**	**66.4**	**10.9**	**13.8**	**12.7**
Season duration (months)	6	10	5	8	5
Yield (kg/ha/yr)	**163,000**	**684,000**	**40,000**	**73,500**	**29,000**

1. Machinery, trellis materials, irrigation equipment
2. NY/Florida requires soil fumigant, -cides, and plastic mulch
3. Includes tractor fuel, water pumping and vent fan operation
4. Assumed same as for Florida.
5. Untrellised, once over harvest
6. Omits energy use in post harvest packaging and treatment