EMSD
European Master in System Dynamics

Residential Rooftop Solar and the Utilities Death Spiral:

A system dynamics analysis of the potential effects of rooftop solar diffusion on utilities' electricity rates and CO_2 emissions

by
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Abstract

U.S. electric utilities are concerned by the recent exponential growth in rooftop solar installations among their customers. They fear that if their customers continue to adopt such self generation technologies and buy less electricity from the utility, then the utility will no longer make enough sales to achieve 'cost recovery' from these customers. Utilities argue that, in order to compensate for this, they will have to increase their electricity rates, and that these rate rises will in turn make self-generation technologies such as rooftop solar even more attractive. Such a situation results in a vicious loop, popularly known as the death spiral, whereby rooftop solar adoption results in rate increases, which in turn leads to more rooftop solar adoption. These rate rises would also be a social problem, as low-income families are statistically the least likely to install rooftop solar, and thus the most likely to suffer these rate rises the most. This study uses a system dynamics model to first analyze the validity of this 'death spiral' hypothesis in the context of residential rooftop solar and, secondly, to evaluate the policy of rooftop solar subsidies, based on their effects on (i) utility rates and (ii) reduction of CO_2 emissions. Simulations reveal that the effect of rooftop solar on both utility rates and CO_2 prevention is highly dependent on whether or not utilities claim/buy Renewable Energy Certificates for these privately owned rooftop solar systems, as part of meeting their Renewable Energy Portfolio. As a case study, the model uses data from the Salt River Project, a public owned utility based in Arizona.

Key words: Rooftop solar, electric utility rates, utilities death spiral, CO_2emissions, rooftop solar subsidies, renewable energy certificates, system dynamics.

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Lastly, I would like to express my heart-felt gratitude to my mother and my late father. I truly appreciate the opportunities that you have provided me with - in education, and in life in general; I only hope that I can put it all to some use!

Foreword

A thesis is quite a large body of information, and a first-time reader can become easily lost whilst wading through it. As such, I have decided to try and make it easier for the reader to keep on track whilst exploring this thesis. This will be done in the following way:

Each paragraph/set of paragraphs will be preceded by a question, to which the paragraph(s) will provide an answer. My goal in doing this is to allow the reader to use the questions as regular points of reference that will serve to easily remind them about the relevance of what they are reading. Additionally, the *sequence* of questions should help the reader to be aware of the (hopefully) logical way in which the information is presented. For example, there is often a sequence of questions whereby each question follows naturally from the response to the previous question. So at one point I ask *'How much residential rooftop solar is there in the U.S.?'* The answer to this begs the next question – '*What has been causing this growth in rooftop solar systems?'* Following this we ask '*How could rooftop solar affect utility rates?*' to which we give a hypothetical answer that begs the next two questions: '*What are utilities saying about rooftop solar?*' and '*What evidence is there to suggest that rooftop solar has affected or will affect utility rates?*'

In addition to helping the reader keep on track, the questions asked in the thesis can also be used to form a kind of 'map' of the thesis, which the reader can review before beginning their reading. The reader will find this 'map' in the table of contents on the next page, with each question appearing under the chapter in which it is found. This map should not only help the reader to preview the way in which the thesis will progress, it should also serve to improve the usefulness of the table of contents, by allowing researchers to more easily access the specific information that they are seeking from this thesis, rather than having to sift through whole chapters.

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1. Introduction

What is the focus of this thesis?

From 2009 to 2014, annual rooftop solar installations on U.S. homes and businesses increased from around 250 MWdc per year to over 1000 MWdc per year [1]. Furthermore, in the reference case of the U.S. Energy Information Administration's (EIA's) Annual Energy Outlook 2014, it is projected that roughly 11% of all electricity generation capacity additions between 2013 and 2040 will be in Solar PV systems. About 60% of these PV systems are expected to be rooftop solar systems (both residential and commercial). This exponential growth in a renewable source of electricity generation has been hailed by some as great news for reducing the industry's CO_2emissions, and thus its effect on global warming. However it has also been causing U.S. electric utilities to become increasingly alarmed, and for the following reason: when customers install their own solar panels, they buy significantly less electricity from the utility. Utilities in regulated markets have argued that, when this happens, they no longer achieve 'cost recovery' from those customers, i.e. they no longer achieve sufficient revenues from that customer in order to meet the costs of serving them (most of which are fixed). In order to compensate for these lost revenues and regain cost recovery, utilities say that they will have to increase their rates (i.e. the price that they charge their customers per kWh of electricity). This increase in the price of electricity from the grid will in turn make self-generation technologies such as rooftop solar even more attractive. As such, U.S. utilities could become caught in a vicious loop, popularly known as the 'death spiral', whereby the reduced demand resulting from rooftop solar leads to an increase in rates, which in turn leads to more uptake of rooftop solar (or other self-generation/energy saving technologies), more reduced demand, a further increase in rates, and so on. The end result, some say, is that it is the poorest customers who are likely to suffer these rate rises the most, as they are the least likely to be able to install rooftop solar (because they are the most likely to live in rented accommodation, for example, or because they cannot afford the upfront costs of solar panels). This idea can be known as the 'cross subsidization hypothesis' as it essentially says that non-solar customers will have to pay higher rates in order to compensate (i.e. subsidize) for the lost revenues that the utilities experience from their rooftop solar customers.

An additional problem is that if utilities' revenues continue to decrease despite rate increases, then this may pose a threat to their ability to maintain important infrastructure such as the grid and dispatchable generation capacities, both of which are used by all customers when the sun is not shining. The effects of rooftop solar on security of supply will not be directly examined in this study, yet the utility's lost profits as a result of rooftop solar diffusion will be examined, and this can be used as a proxy for this security of supply issue.

This study uses a system dynamics model to first analyse the validity of the 'death spiral' and 'cross subsidization' hypotheses as they apply in the context of residential rooftop solar. In light of this, the model is then used to evaluate three policies concerning rooftop solar – (i) rooftop solar subsidies, (ii) special rate plans/charges for rooftop solar customers, and (iii) the utility's use/non-use of the Renewable Energy Certificates (RECs)[i] arising from their customers' rooftop solar systems, as part of the utility's Renewable Portfolio Standard (RPS)[ii]. These policies are evaluated based on their effects on (i) utility rates and (ii) reduction of CO_2 emissions. Utility rates can be considered a social issue for policymakers, whilst CO_2 emissions represent the environmental aspect at play.

How will this thesis contribute to the existing literature on rooftop solar?

The study makes a contribution to the existing literature surrounding rooftop solar in the U.S. by adding to the literature on the death spiral. It will also have a contribution to rooftop solar diffusion studies, by including the effects of the feedback loops that exist between rooftop solar diffusion and utility rates. To my knowledge, the effects of these feedback loops have been lacking in all but one other study looking at rooftop solar diffusion, and this study focused on an Australian electricity market [2].

The paper will also make a contribution by focusing specifically on how the existence and use of RECs is a major factor in determining the effects of rooftop solar (and its subsidies) on both utility rates and prevention of CO_2 emissions.

Will the results of this thesis be applicable to all U.S. electricity markets, or only to some?

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[i] An REC is a tradable right to claim the environmental and other attributes associated with 1 megawatt-hour of renewable electricity from a specific generation facility.' [87].

[ii] An RPS is a sometimes legally enforceable requirement for electric utilities to meet a certain percentage of their customers' demand through renewable generation sources, by a certain year. While RPS requirements differ across states, there are generally three ways that electricity suppliers can comply with the RPS:
1. Owning a renewable energy facility and its output generation.
2. Purchasing Renewable Energy Certificates (RECs).
3. Purchasing electricity from a renewable facility inclusive of all renewable attributes. [87].

As a case study, this thesis uses data from the Salt River Project (SRP), a public owned utility based in Arizona. As such, the model simulations will be applicable only to this utility. Although SRP is a publicly owned utility, much of its rules of operation are almost identical to that of regulated investor owned utilities, which are the most common kind of electric utility in the U.S [3]. The main difference is that while most regulated utility's have their rates regulated by a commission, SRP has its rates determined by its own publicly elected board of directors [4]. As such, the structure of the model, and the insights arising from it, can be considered as roughly applicable to most U.S. regulated electric utilities. However it should be noted that SRP is a relatively extreme case, as Arizona has particularly suitable conditions for solar energy[iii].

How will this thesis be presented?

This introductory chapter has defined the topic and scope of this thesis, and the following chapter will develop the background to the problem. In Chapter 3, the perspectives of different stakeholders will be explored. Chapter 4 reviews and justified the method of analysis used to explore the topic of this thesis. Chapter 5 presents the model, first through CLDs, and then as the stock and flow model used for simulations. Chapter 6 is devoted to model validation, whilst Chapter 7 looks at model simulations in the reference case. The model is then used for policy analysis in Chapter 8. Chapter 9 reveals the limitations of this work, and lists my recommendations for further work on this topic. In the 10th and concluding chapter, I will present the main findings of the thesis, and discuss the take-away messages for two of the stakeholders to this issue – the U.S. government and electric utilities.

[iii] For example, according to the NREL's PVWatts calculator, a 4kW rooftop solar system in Arizona is expected to produce 6919 kWhs a year, whilst the same sized system would only produce 5100 kWhs (26% less) a year in Newark, New Jersey [72].

2. Background

How much residential rooftop solar is there in the U.S.?

In 2014, capacity in solar technology accounted for 1.13% of the U.S.'s total electric generating capacity, and supplied .4% of that year's electricity consumption in the U.S. [5]. Half of this solar generation came from customer-sited PV systems [6], or what will be referred to as 'rooftop solar systems', which are PV systems owned/rented by utility customers, and which are usually installed on the rooftop of the home or business of that customer. In this study the focus will be on residential rooftop solar, thus excluding the rooftop solar systems owned by small and large commercial utility customers. If we presume that in 2014 roughly half of these privately owned solar systems were residential rooftop solar systems, then we can say that about .1% of electricity demand was met by residential rooftop solar output in the U.S. in that year.

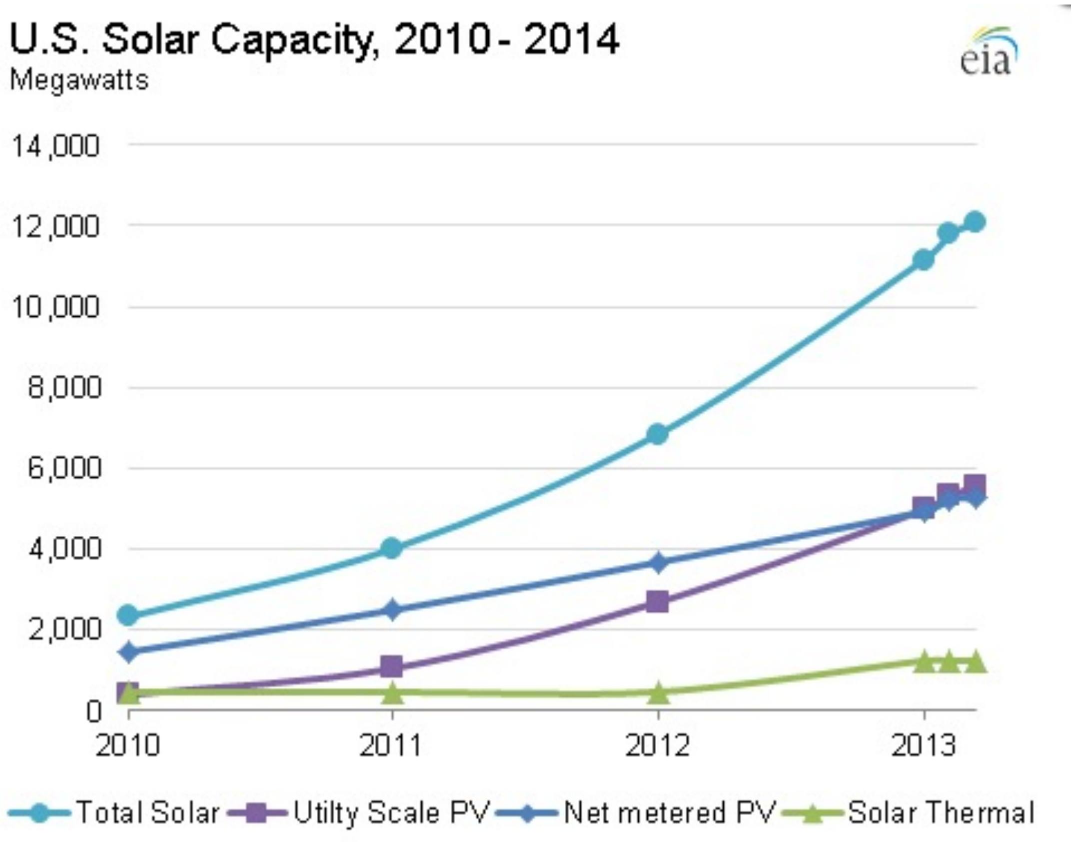

Figure 1 - cumulative installed solar capacity (MWs) in the U.S.; Net-metered PV refers to residential and commercial rooftop solar. Data taken from reference [7].

Yet although residential rooftop solar only accounts for a small amount of current generation in the U.S., it is expected that its presence will become stronger and stronger over the years to come. In the reference case of U.S. Energy Information Administration's (EIA's) Annual Energy Outlook 2014, it is projected that roughly 11% of all electricity generation capacity additions between 2013 and 2040 will be in Solar PV systems. It is also projected that 60% of these PV systems will be rooftop solar systems (both residential and commercial). If residential rooftop solar accounts for roughly half of this capacity, then we can say that it is projected to account for roughly 3.3% of capacity additions between 2013 and 2040 [8].

What has been causing this growth in rooftop solar systems?

The main factors causing the recent and projected growth in rooftop solar systems are likely to have been (i) falling PV system costs, due largely to solar's steep learning curve [9,10], and (ii) subsidies for rooftop solar installers. These subsidies include the Residential Renewable Energy Tax Credit, which gives rooftop solar installers a tax credit equal to 30% of the final installed price of the system [11]. Additionally, rooftop solar users in 43 U.S. states and several districts benefit from a subsidy known as Net Metering, whereby all of the excess electricity produced by their system (i.e. all electricity produced by the panels at any moment but not used by the household/business at that moment) will be exported to the grid, in return for credits on their next monthly bill from the utility. For some utilities, such as SRP, credits for this excess electricity are equal to the retail price [12]. However, Net Metering for other utilities allows them to give a credit equal to just the perceived avoided costs made possible by the exported electricity [13].

There are also two non-financial factors that are likely to have played a big role in the growth of rooftop solar systems. In a 2014 survey, 48 residential rooftop solar installers were asked to reveal their motivations for having the system installed. 31 of these said that environmental concern was a motivating factor in their decision, while demonstration of innovation and/or technical interest was cited by 34 respondents, making it the most commonly cited motivating factor in the study [14].

How could rooftop solar diffusion affect utility rates?

Most U.S. electric utilities operate in a regulated market, and so their rates are determined under the principle of 'cost recovery', rather than by spot markets, as they would be a deregulated market. Cost recovery essentially means that a utility will be regulated to charge a rate that will gather them sufficient revenue in order to (i) continue meeting the costs of providing service to the customers in their service area, whilst (ii) making a reasonable rate of return for its investors [15,16].

Thus the way in which such a rate is determined by utilities (i.e. a rate that will achieve cost recovery) can be roughly represented by the following simple equation [16]:

Cost of providing service to customers*reasonable rate of return for investors ($) / Expected demand from customers (kWhs) = a price ($) per kWh

As such we can see that in SRP's context (as well as the context of most regulated utilities), when the expected demand for a utility's electricity falls (as a result of rooftop solar diffusion, for example) and costs remain the same or do not decline sufficiently, then utilities will have to (or at least will be allowed to, by their own regulators or board of directors) charge higher rates in order to maintain 'cost recovery'. This is because the utility's costs will have to be spread over fewer kWh sales. This can be seen in the equation shown, as we see that the bottom of the fraction will become smaller from the reduced demand (resulting from rooftop solar use), and if the top of the fraction does not reduce sufficiently, then a higher price per kWh will be chosen.

Part of the reason that reduced demand will result in lost profits is due to utilities' rate structures. Most U.S. utilities have rate structures that are designed to collect the bulk of revenue through volumetric charges[iv], whilst the majority of their costs are fixed [15,17,18]. As such utilities argue that a significant drop in demand from rooftop solar customers could result in some of the utility's fixed costs being under recovered [15,18–20]. This has also been argued in academic studies [17].

[iv] This is in order to protect low-income and low-usage customers, and to encourage energy conservation by high consumption customers [31,88].

3. Literature Review

What are utilities saying about rooftop solar?

The majority of U.S. electric utilities and their representatives seem to perceive rooftop solar diffusion as a threat, based on the perception that they will not achieve cost recovery from customers who install rooftop solar panels or other distributed energy resources (DERs). The Edison Electric Institute, which represents all U.S. investor-owned electric utilities, issued a report in 2013 saying that:

'*The regulatory paradigm that has supported recovery of utility investment has been in place since the electric utility industry reached a mature state in the first half of the 20th century. Until there is a significant, clear, and present threat to this recovery paradigm, it is likely that the financial markets will not focus on these disruptive challenges, despite the fact that electric utility capital investment is recovered over a period of 30 or more years (i.e., which exposes the industry to stranded cost risks). However, with the current level of lost load nationwide from DER being less than 1 percent, investors are not taking notice of this phenomenon, despite the fact that the pace of change is increasing and will likely increase further as costs of disruptive technologies benefit further from scale efficiencies.*' (page 1, of reference [21])

However, since 2013 some U.S. electric utilities *have* seemingly begun to take action concerning rooftop solar. Several utilities have imposed/proposed either a special rate plan or a special charge for their rooftop solar customers [20,22,23]. For example, both SRP and Arizona Public Service Company (APS) (Arizona's largest electric utilities) have proposed changes in the rate plans of their rooftop solar customers that would add roughly $50 to the monthly bill of a typical solar customer [24]. SRP's board of directors approved this proposal, but allowed all existing solar customers to be grandfathered from these changes for 20 years [25]. In response to this policy, Solar City (one of the leading rooftop solar installations companies in the U.S.) has recently filed a lawsuit against SRP, stating that it was engaging in 'anti-competitive behaviour' [26].

APS' regulator, the Arizona Corporation Commission, partially rejected APS's proposal and instead allowed an average increase of just $5 a month for their solar customers [18,22]. However, APS has recently made another proposal to increase this charge to $21 a month, the results of which are pending [22]. Such proposals are likely to become more common in other parts of the country as rooftop solar spreads.

In addition to fighting for special rate plans for their solar customers, many utilities and their representatives have also called for an end to the subsidy of net metering, which they say overvalues the electricity that utilities are forced to 'buy' from the their rooftop solar customers [21,27–29]. They also argue that the two way flow of electricity that net metering is based on incurs some extra costs for the utility, as the grid was originally designed for a one-way flow [30,31]. The end result is increased costs and thus reduced profits for the utility, which they argue will result in them having to charge higher rates, meaning that there will be some cross subsidization of solar customers by non-solar customers.

For example, APS testified to the Arizona Corporate Commission in July 2013, saying that for every installation of a rooftop solar unit, between $800 and $1000 was shifted in costs to the remaining non-solar customers [18,19]. This is in stark contrast to the claims made in a report commissioned by the Solar Energy Industries Association (SEIA), which said that installations of rooftop solar in APS's service area had benefits for APS customers that exceeded the costs 'by more than 50%, with a benefit / cost ratio of 1.54' (Page 2, of reference [32]). This goes to show how much uncertainty, and perhaps bias, there may be in the financial assessments of both (or either) utilities and rooftop solar advocates.

However it seems that not all U.S. electric utilities perceive rooftop solar as a threat –NRG's[v] CEO, David Crane, has recently made plans to change the company's business model and become the leading distributed generation provider, looking to bypass the traditional utility business model [33,34]. However it should be noted that NRG operates as a deregulated utility [35], and so their business model (of providing only distributed energy resources) would not be possible for regulated utilities. This is because regulated utilities are charged with the responsibility of always meeting demand [16]. Under current technology this would require them to also invest in the grid, as well as dispatchable forms of generation such as coal and natural gas plants.

What evidence has there been to suggest that rooftop solar diffusion has affected or will affect utility rates?

To this author's knowledge one of the clearest pieces of evidence suggesting that rooftop solar diffusion has already affected at least one U.S. electric utility's rates can be seen in APS' 'lost fixed cost recovery' charge. This charge is designed to recover 'a portion of unrecovered fixed costs resulting from energy efficiency and distributed generation programs' [36], the latter of which includes rooftop

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[v] A U.S. electric utility serving over 3 million customers in over 50 states [89].

solar. The charge applies only to residential and small business customers because large commercial and industrial customers have rate structures that already include the recovery of fixed costs [36]. Currently, this charge will increase the monthly bills of these customers by 1.46% [36,37]. Given that this charge reflects both distributed generation *and* energy efficiency programs, and given that it currently increases the monthly bills of some customers by just 1.46% in one of the most solar-penetrated markets in the U.S., it seems fair to say that distributed generation alone is not currently causing any significant increases in the monthly bills of non-solar customers. However this may change under scenarios of higher rooftop solar penetration.

Indeed, evidence in markets with much higher levels of distributed energy penetration, such as the Australian and particularly German market, has shown that distributed generation resources could have a significant effect on the price of electricity. In these markets, policies such as net metering as well as heavy subsidies to renewables and demand-side management have been said to be causing big problems for the traditional utilities there [21,38–41]. RWE, Germany's second largest utility, has been saying since 2013 that its declining profits and forced shutdown/mothballing of capacity has been in large part caused by the reduced demand brought about by intermittent subsidized renewables such as rooftop solar [42]. In 2013, RWE announced that it will take 3100 MWs of capacity offline in Germany and the Netherlands and will also dispose of 1200 MWs of German coal-fired capacity to which it has contractual usage rights [43]. Taking this dispatchable capacity offline could have serious repercussions for Germany's ability to meet future demand[vi]. The fears of not being able to meet demand on cloudy, windless days has spurred the German government to consider starting a capacity market that would subsidize unprofitable power plants, thus allowing them to stay open and provide power when renewables can't [44].

These subsidies, as well as the direct subsidies for solar customers, are gathered through additions to utility's rates [45]. As such, one could speculate that the high level of rooftop solar diffusion in Germany could be part of the reason for the country having some of the highest electricity rates in Europe [46]. Indeed in 2013, over half of the capacity in Germany's two largest renewable sources of energy, wind and solar, was owned by individuals, farmers and industry actors, whilst just 5% was owned by big utilities and 7% by regional/municipal utilities [47]. Thus it is clear that whilst distributed customer-owned generation has been a major factor in the success of Germany's energy transition, it has also been a major recipient of the renewable subsidies that have been gathered from increased electricity prices there.

[vi] However one should note that Germany's current market is in a state of oversupply, and so their reserve margin may remain sufficient for the time being, at least until all nuclear capacity is forcibly turned off in 2022 [90].

Does rooftop solar affect any other stakeholders, apart from utilities?

Yes – if rooftop solar does increase rates, then it is the poorest members of society that are most likely to feel the effects of this the most. This is because low-income households are statistically the least likely to install rooftop solar, as can be seen in figure 2 below.

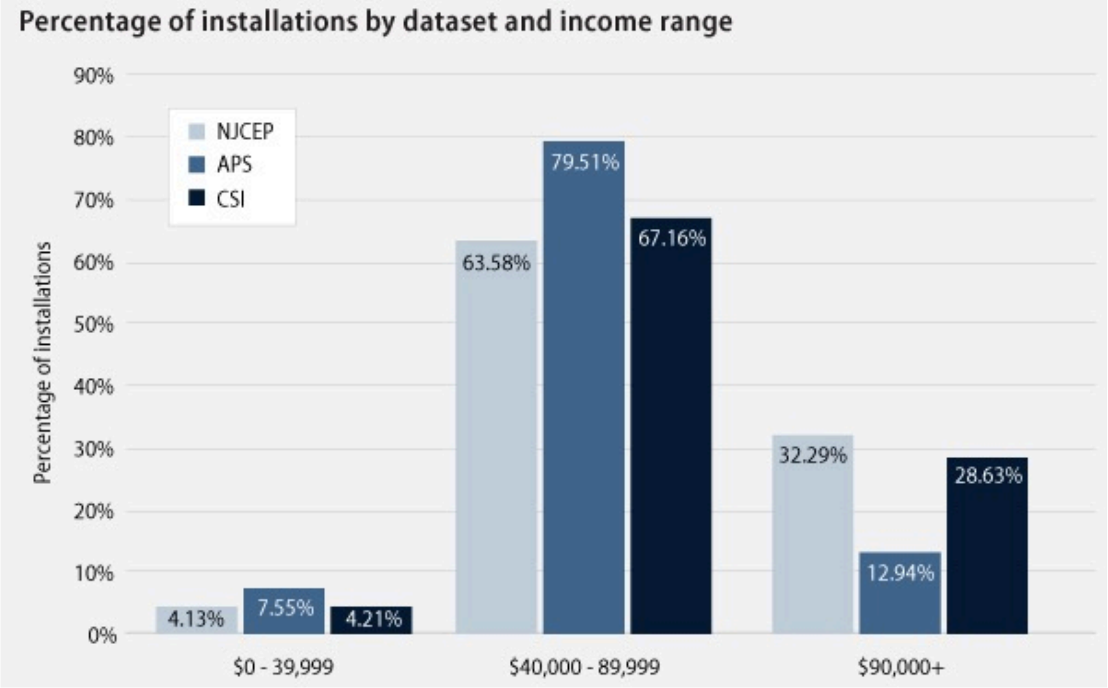

Figure 2 - Rooftop solar installations by income range, as revealed in three different databases for the U.S.[vii] Sourced from reference [48].

There are three theoretical explanations for why lower income households are not installing rooftop solar as much as middle and upper income zip codes. Firstly, they are the most likely to live in rented accommodation, which discourages the long-term investments of having solar panels installed. Secondly, they are the most likely to live in apartments rather than houses, which have little/no privately owned roof space. Lastly, they are the most likely to be unable to afford the upfront investment costs that are sometimes necessary for rooftop solar instalments. As regards this last reason, it should be noted that new financing options offered by rooftop solar installation companies are reducing the problem of having to make an upfront investment [48]. Additionally, a new

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[vii] Data limitations of this graph should be noted as it uses 'median income data at the ZIP-code level from the U.S. Census Bureau because actual income data for each installation are not publicly available. There is an inherent amount of uncertainty in using median income data as proxies for real income data, as actual incomes associated with each installation could be higher or lower than the median income' [48]

government program in California 'offers affordable housing projects higher incentives than standard market rate housing projects' [49]. Yet this still does not solve the problem that only those living in houses instead of apartments can install rooftop solar, and that renters are less likely than homeowners to make the investment in rooftop solar panels.

All members of society, ratepayers or not, could also be affected by rooftop solar diffusion if it begins to cause problems for security of supply. This is because an increasing reduction in utility revenues could make it difficult (in a regulated market) or unattractive (in a deregulated market) for them to maintain essential infrastructure such as the grid and dispatchable generation technologies, both of which will almost certainly be needed in the coming decades (given that storage options for renewable energies remain uneconomic at a large scale for the time being).

What are the perceived benefits of rooftop solar, and who benefits from it the most?

The most obvious benefit of rooftop solar is that its output generally displaces that of fossil fuel plants, and thus reduces the CO_2 emissions[viii] arising from these plants [50]. This benefits the planet at large. As already stated, in 2013 over half of the capacity in Germany's two largest renewable sources of energy (wind and solar) was owned by individuals, farmers and industry actors, whilst just 5% was owned by big utilities and 7% by regional/municipal utilities [47]. As such it is clear that distributed customer-owned generation has been a major factor in Germany's highly successful renewable energy transition, and thus a major contributor to the fight against climate change.

Rooftop solar can also be said to have the following benefits for other stakeholders:

- It benefits those who install it, as they often achieve a positive return on their investment.
- It benefits the economy by creating jobs [51].
- It increases security of supply in the face of downed power lines [51].
- It creates a sense of environmental action amongst citizens, as well as a sense of freedom in choosing how their energy is produced.

[viii] It should also be noted that energy is used in the production of PV systems, and that this energy use causes some CO_2 emissions. However the overall effect of producing a PV system is that it prevents far more CO_2emissions than it creates, with between 87 and 97% of the energy produced by a PV system having no effect on pollution, greenhouse gases, and depletion of resources [91].

- It increases competition in a previously monopolised market, which could (all else equal) benefit all ratepayers eventually. Indeed, some feel that the continuingly rapid spread of rooftop solar will give the utility industry a much-needed jolt towards updating its century old business model [52]. The International Energy Agency (held by many as the world's leading think-tank on energy issues) also feels that such a change in business model is going to be necessary for utilities, whether they like it or not [53].
- It helps utilities to avoid some costs, such as fuel costs. As will be discussed later in the model description, these avoided costs could potentially outweigh lost revenues in some scenarios.

Overall then it is clear that the growth of rooftop solar is clearly seen from many perspectives, some of which are positive and some of which are negative. A useful review of these perspectives is provided below, in the form of a first person statement that may represent the viewpoint of each stakeholder:

- **Most Utilities**: '*Rooftop solar will kill our profits!*' (via reduced revenues)
- **Some Utilities**: '*Time to change our business model!*' (by providing distributed generation resources)
- **Rooftop solar installers/customers**: '*Utilities are trying to kill us, their only competition!*' (via the special rate plan for solar customers)
- **Non-solar customers**: '*We are subsidizing the solar customers!*' (via the addition in rates made necessary by rooftop solar)
- **Environmentalists**: '*How many CO_2 emissions does rooftop solar diffusion prevent*?' (via replacement of fossil fuel plant output)

That concludes our review of the introduction and background to this thesis. In the following chapter we will analyse the choice of method used to analyse the topic of this thesis.

4. Methodological Review

What is system dynamics and in what ways is it a suitable method for dealing with the topic of this thesis?

System dynamics is an interdisciplinary methodology that uses computer simulations in order to increase understanding of complex dynamical systems [54]. The typical goal of a system dynamics study is to use models to generate insights in to how proposed policies might affect a certain problem, whilst maintaining awareness of the effects of that policy on the wider system in which the problem is embedded. System dynamics models focus on replicating the qualitative behaviour of a system, rather than seeking exact numerical mimicry of that system [54]. To replicate this qualitative behaviour, system dynamics models have a much stronger focus on the endogenously generated behaviour in a system (i.e. behaviour which is a result of cause and effect relationships within the considered system boundary), rather than behaviour that results from exogenous forces (i.e. forces outside of what is considered the system boundary).

In most decision making contexts, there is said to be two kinds of models that one could use – (i) automation and optimization models, and (ii) thinking and decision support tools [55]. The former kind of models are most suitable for situations which involve routinized decisions that involve little human interaction, whereas the latter are more suitable for problems where the uncertain variable of human behaviour plays a role, and where there is no clear optimal solution to the problem. System dynamics falls into this latter category, as it is a useful method for dealing with uncertainty and complexity. System dynamics is particularly useful in aiding the understanding of systems that contain causal structures/relationships known as feedback loops, delays, and nonlinearities.

It is perhaps for this reason that system dynamics has been widely used in the electricity supply sector [56], as this industry contains plenty of feedback loops, delays, and nonlinearities, as well as regular influence from human action and decision making. In the case of this study, for example, there is a feedback effect between rooftop solar diffusion and electricity rates, a delay between lost revenues and rate increases, and a nonlinear relationship between rooftop solar's payback period and the number of SRP customers who adopt it each year (thus representing a human decision making process). Presence of such feedback loops, delays, and/or nonlinearities in a system has been shown to significantly limit people's ability to manage that system and predict how it will behave [57], and it is for this reason that computer simulations could prove to be a useful methodology in tackling this subject.

Indeed in the case of the last potential 'death spiral' to happen to U.S. utilities (which occurred mainly due to increasing lead-times for generating capacities, as well a reduction in the growth rate of demand), Andrew Ford has argued that system dynamics was the only modeling method used by utilities that could successfully simulate the effects of the feedback structure between electricity rates and demand, which was at the heart of that potential death spiral [58]. The result, Ford argues, is that system dynamics played an essential role in generating the insights and system understanding that eventually helped utility managers to prevent this death spiral [58]. As such, it seems likely that system dynamics could also prove useful in analyzing and providing insight concerning the current 'death spiral', as it has quite a few similarities to this previous situation.

Thus it is for the reasons stated above that system dynamics has been chosen as the method of analysis for this thesis.

5. Model Description

What is the purpose of the model and how does it fulfill this purpose?

The purpose of the model is to determine the effects of rooftop solar diffusion on (i) SRP's rates for residential customers, and (ii) prevention of CO_2emissions arising from electricity production in SRP's service area. The model will also represent rooftop solar diffusion among SRP's customers. However the main focus will be on electricity rates and prevention of CO_2emissions.

The model is essentially composed of two parts. The first part (seen in figure 3) represents the three main reinforcing feedback loops that drive rooftop solar diffusion. One of these reinforcing feedback loops (R1) represents the 'death spiral' hypothesis as it relates to residential rooftop solar. It shows how the lost revenues resulting from this rooftop solar diffusion causes an increase in SRP's residential rates, which in turn causes greater rooftop solar diffusion among residential customers.

The second part of the model (presented from figure 4 up to figure 7) represents (some of) the avoided costs that SRP benefits from as a result of rooftop solar diffusion, and how these, all else equal, will reduce SRP's rates and thus discourage the diffusion of rooftop solar. In this model we look only at the avoided variable costs and avoided generation capacity investment costs made possible by rooftop solar. The effects of rooftop solar diffusion on the utility's grid costs are ignored in this model. This is because it seems that there does not yet exist a proper method of analysis for quantifying the change in grid costs attributable to rooftop solar diffusion [29].

The model will first be presented through causal loop diagrams (CLDs), followed by discussion of the most important feedback loops in each CLD. Following this, the more detailed stock and flow diagram will be presented.

How does the model represent the effect of rooftop solar on utilities rates, and the problem of the death spiral?

Below we see a CLD of the three main reinforcing feedback loops that affect rooftop solar diffusion. R is used to denote reinforcing loops in these CLDs, whilst B will be used to denote balancing loops. Additionally, the term 'Utility' has been used in place of SRP so that a more generically applicable understanding can be achieved by these CLDs.

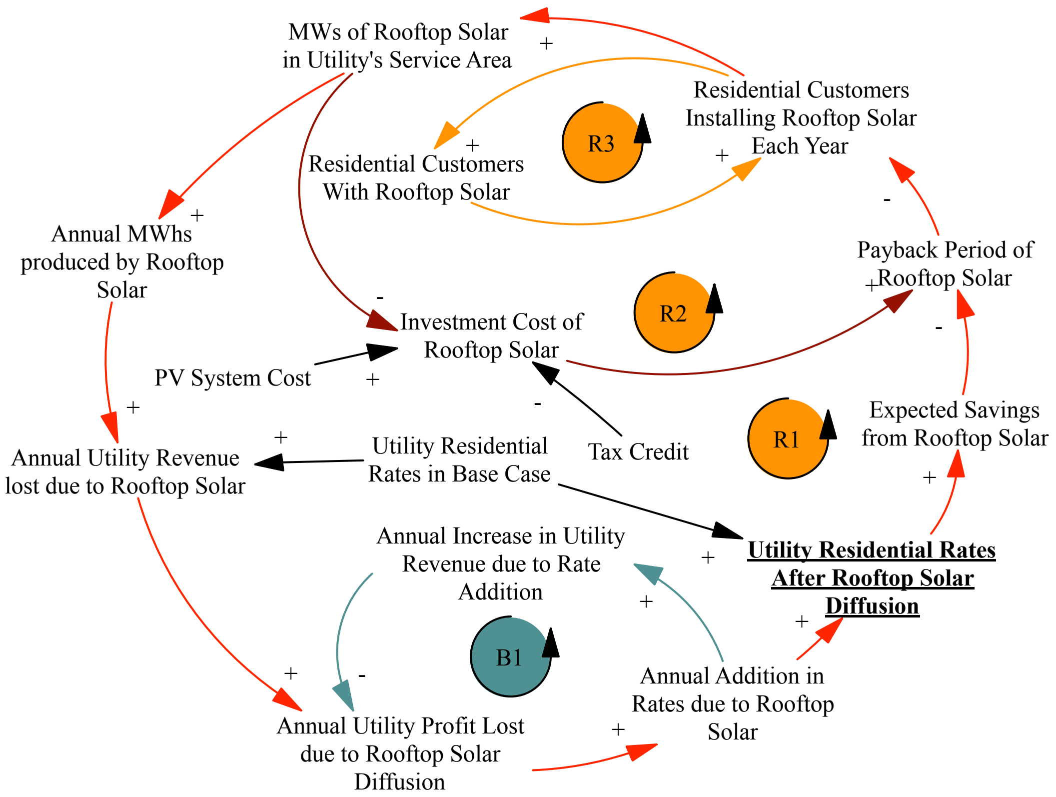

Figure 3 - CLD representing the feedback loops driving rooftop solar diffusion, and the resulting effects on the utility's rates.

Loop R1 (outer red loop): This loop represents the death spiral hypothesis. For every SRP residential customers that installs a rooftop solar system, SRP lose some revenues. This is because rooftop solar panels installed by residential customers produces a certain number of MWhs per year (quite a lot in sunny Arizona) and these MWhs replace those MWhs that the rooftop solar customer would have bought from SRP. As such, SRP make less sales of its product and its revenues are reduced.

In the CLD we see that the 'annual revenue lost…' will increase the 'annual profit lost…', which in turn increases SRP's rates. This represents the fact that the rates that SRP charges are determined under the principle of 'cost recovery', which has already been explained in Chapter 2. This essentially means that any lost profits for SRP will result in them charging higher rates.

Finally, we note that a raise in SRP's rates will increase the expected savings that potential rooftop solar adopters would expect to make from their investment. This in turn will reduce the expected payback period[ix] of their investment, which

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[ix] The payback period means the number of years that it will take for the money saved via the rooftop solar system to exceed the cost of the investment in that system. So if the rooftop solar

will therefore increase the number of residential customers installing rooftop solar each year.

Loop B1: This loop has the opposite effect of the R1 loop. It represents the fact that the addition in rates due to rooftop solar will result in some increased revenues for SRP (all else equal). This in turn will decrease their profits lost due to rooftop solar, which will reduce the addition in rates needed in the next year.

Loop R2: This reinforcing loop represents the fact that provision of rooftop solar is a relatively young industry. As such, it is likely to experience some increases in efficiency as it gains more experience. For example, the administrative processes required to connect rooftop solar systems could become increasingly streamlined as more and more rooftop solar systems are installed. This reduces the time, effort and resources that rooftop solar installation companies need for each installation. This in turn allows them to charge a lower price to their customers, who thus benefit from a lower investment cost for having panels installed. This investment cost is also decreased by the exogenously determined global PV system cost, which is likely to be the main driver of reductions in hard costs (i.e. the costs of the panels themselves). Solar technology is still a young technology, and one experiencing significant cost reductions as it grows [59]. As such we can expect the price of solar panels to continue to decline over the years to come, although the rate of this decline is hard to predict.

The model also represents the 30% tax credit that was introduced in 2006 and which has been extended until 2016 [11]. This policy gives residential customers who buy a distributed PV system (amongst other technologies) a tax credit that is equal to 30% of the final price paid for the module (i.e. including system and installation costs). Whether or not this tax credit is renewed in 2016 remains to be seen, and as such it can be treated as a policy variable in the model.

Loop R3: This loop represents the 'word-of-mouth' effect that is often found in models representing the diffusion of a new technology [60–62]. The word of mouth effect in regards to rooftop solar diffusion in particular has also been validated through survey evidence [14]. This effect essentially says that as more and more people adopt a certain technology, their friends, family and neighbours will become more aware of the technology and so will become more likely to adopt it themselves. This further increases the stock of adopters, and so further increases the word-of-mouth effect. Such a phenomenon has been found to be a driver of the exponential growth often experienced by young technologies [61]. However, this exponential growth will eventually lead the system to a point whereby the

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system is expected to save you on average $200 a year, and the investment cost was $2000, then the expected payback period of that system would be 10 years.

potential stock of adopters is smaller than the actual stock of adopters, meaning that the growth rate of the stock of adopters will start to decline. Thus the typical behaviour pattern of a system governed by a word-of-mouth effect is S-shaped growth (exponential growth followed by exponential decay).

How does the model represent the avoided costs that utilities can benefit from as a result of rooftop solar?

The CLD below represents the avoided generation capacity costs that SRP can benefit from as a result of rooftop solar diffusion.

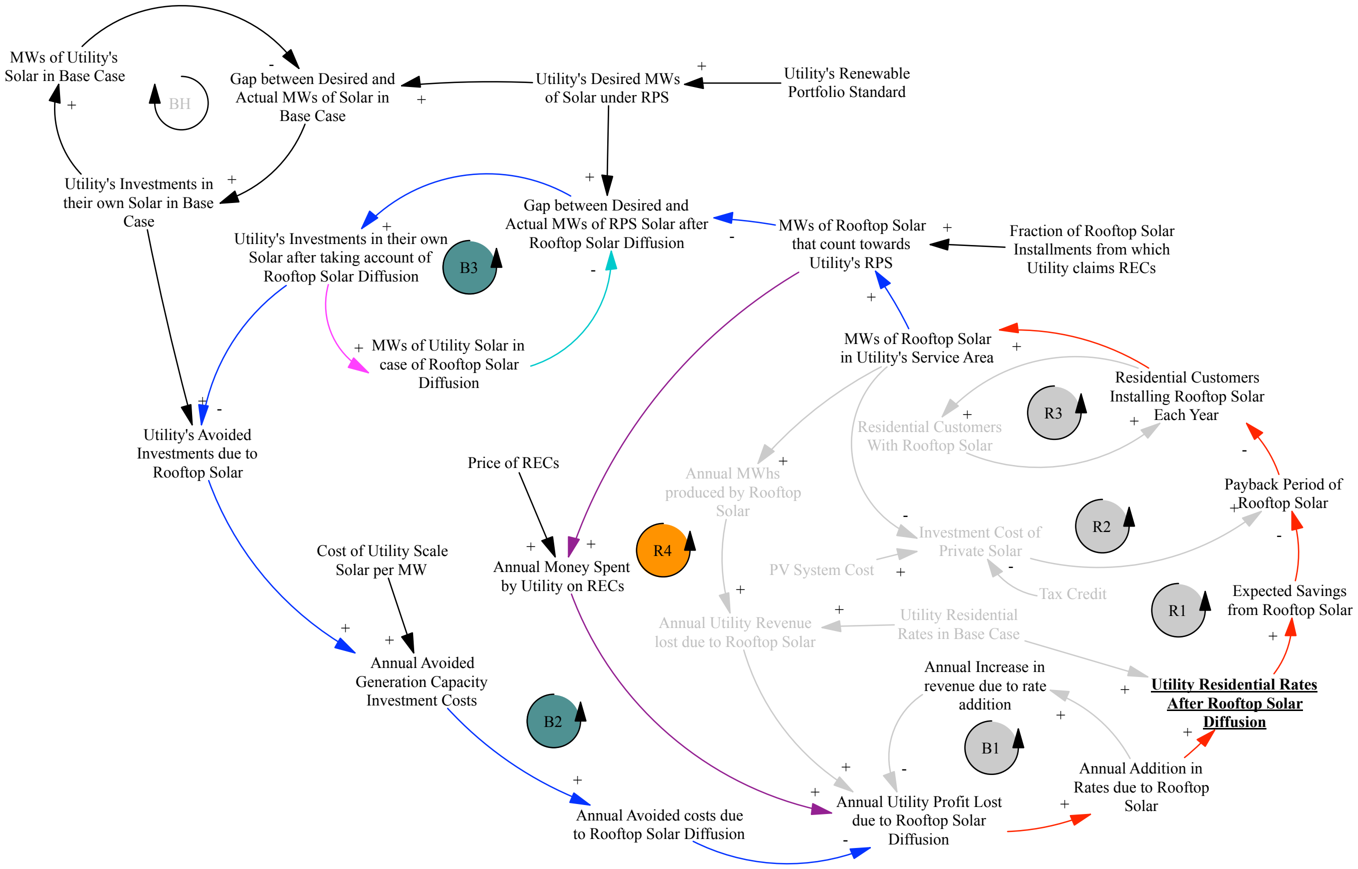

Figure 4 - CLD representing the utility's avoided generation capacity costs.

Loop B2 (Blue to Red Loop): This loop represents the avoided generation capacity investment costs that the utility can benefit from due to rooftop solar (see assumption 1 on page 25). This loop is based on the idea that SRP, like most utilities, operates with a renewable energy portfolio standard (RPS), and that part of this RPS can be met through the use of renewable energy certificates (see assumption 2 on page 25). Thus the model assumes that SRP can enter into a contract with their rooftop solar customers in order to claim the RECs from their systems. Claiming these RECs would allow the utility to balance its investments in its own solar which would otherwise be necessary to meet their RPS (see the stock and flow description on page 36 for more on this). These annual avoided generation capacity costs then reduce the 'Annual Profit Lost due to Rooftop Solar', which in turn reduces SRP's rates. This eventually reduces the number of customers installing rooftop solar each year, which, to close the loop, slows down the growth of the 'MWs of Rooftop Solar in Utility Service Area'. The meaning of this loop is essentially that, all else equal, rooftop solar diffusion will allow SRP to avoid some generation capacity investment costs, which in turn should (a) reduce SRP's rates and thus (b) cause less solar diffusion. This means that rooftop solar diffusion is caught in a balancing loop.

Loop BH: To determine how many investments in their own solar have been avoided, we need to know what investments SRP would have made each year *if there was no* rooftop *solar diffusion* (note that this is a hypothetical situation, and so for this reason this loop has been termed BH, to alert the reader to the fact that it does not refer to any actual loop that exists in the system[x]). The purpose of this loop is to help us determine the 'Utility's Avoided MW Investments due to Rooftop Solar', by seeing the difference between the utility's annual investments in the case of no rooftop solar diffusion (called the Base Case) and their annual investments in their own solar '…after taking account of Rooftop Solar Diffusion' (in the RS Case). Note that if the utility does not claim or buy any RECs from their customer's rooftop solar systems, then the difference between their base case investments and their investments after taking account of solar will be zero, and so SRP will not avoid any capacity investment costs.

Loop B3 (Blue to Pink to Turquoise Loop): This balancing loop represents the fact that as SRP invest in their own solar, they increase their stock of solar and come closer to reaching their RPS solar goal, which in turn reduces the investments needed in the next year in order to meet that year's goal.

Loop R4 (Red to Purple Loop): This reinforcing loop represents the fact that the RECs from rooftop solar systems belong to the system owner (i.e. the SRP solar customer) and so for SRP to claim these RECs it would have to buy them (see assumption 6 on page 26). This in turn would reduce its profit, which would eventually cause an increase in rates, greater rooftop solar diffusion, a greater stock of MWs from which SRP buys RECs, and so, to close the loop, a greater number of RECs for which SRP pays. Note that this reinforcing loop acts in exact

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[x] This hypothetical loop is necessary in this model because we are not modelling all of SRP's capacity investments and their associated costs. If we were, then we would be able to determine the avoided costs due to rooftop solar by first simulating a scenario of no rooftop solar diffusion, looking at the investment costs, and then simulating a scenario with rooftop solar diffusion, and seeing the extent to which the investment costs have been reduced. Such simulation results are not possible in this smaller model, unless we use this hypothetical loop.

opposition to the B1 loop, which allows SRP to avoid costs based on the stock of rooftop solar systems.

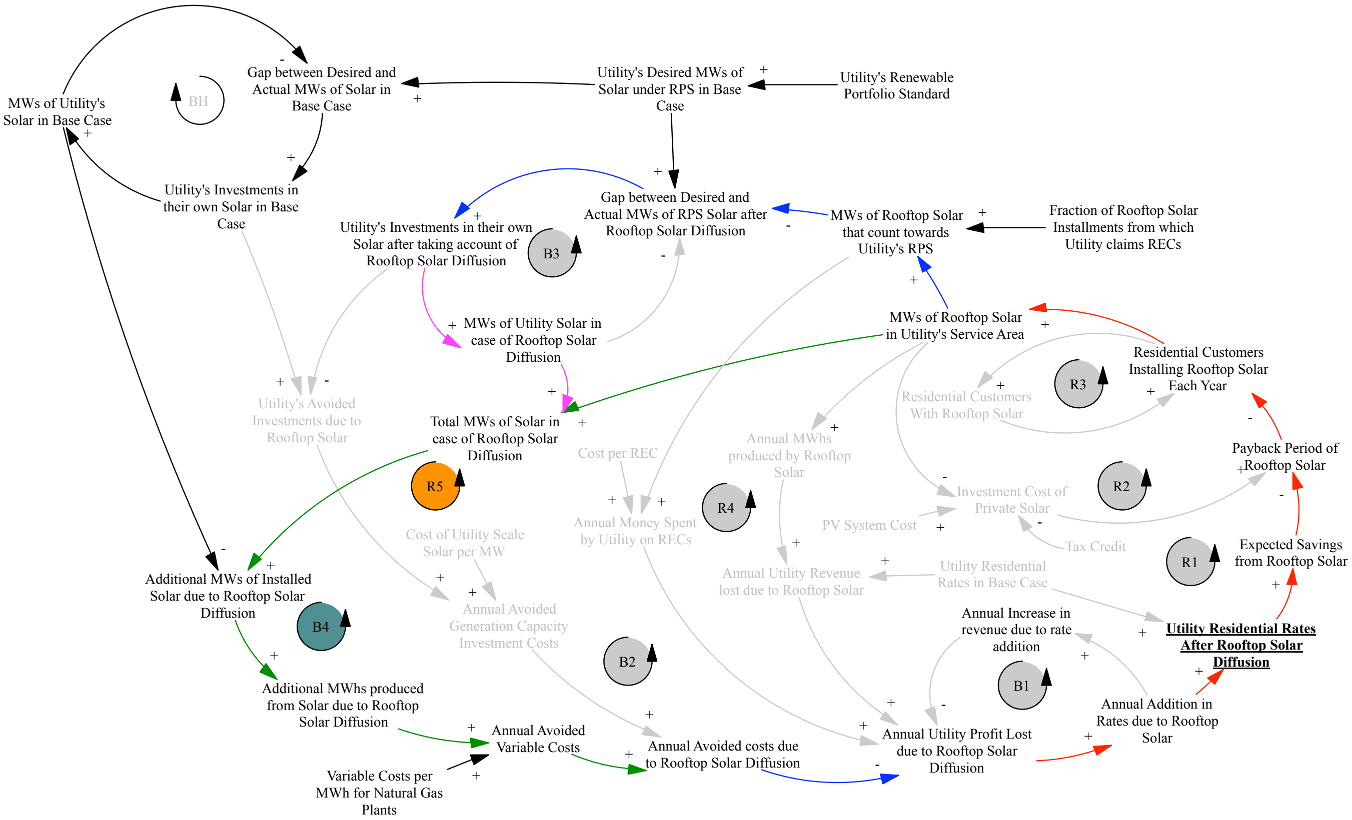

Figure 5 - CLD representing the avoided variable costs made possible by rooftop solar

Loop B4 (Red to Green Loop): This balancing loop represents SRP's avoided variable costs due to rooftop solar diffusion. We assume that all solar generation technology allows for avoided variable costs that would arise from natural gas plant generation[xi] (see assumption 11 on page 27). This loop essentially says that every MW of rooftop solar increases the difference between the MWs of solar that are present in SRP's service area in the RS case (i.e. in the case of rooftop solar diffusion), and the MWs of solar that would be present in the Base Case. These 'additional' MWs in turn increases the additional MWhs produced by solar in SRP's service area. These MWhs in turn displace natural gas plant use, resulting in some avoided variable costs for SRP. Once again these avoided variable costs reduce the profit lost due to rooftop solar, which reduces rates, reduces rooftop solar diffusion, and so finally, to close the loop, slows the growth of rooftop solar in SRP's service area.

[xi] Around 87% of these natural gas plant variable costs are fuel costs, whilst the remaining 13% is split between operation and maintenance costs [92]

Loop R5 (Red to Blue to Pink to Green Loop): This reinforcing loop goes against the B3 loop. It represents the fact that if some of the rooftop solar systems cause SRP to balance its investments in its own solar (via RECs), then there will be less MWs of SRP's solar. This will mean that the 'Total MWs of Solar in case of Rooftop Solar Diffusion' will be less than otherwise, which means that the 'Additional MWs of Installed Solar due to Rooftop Solar Diffusion' will be also be less than otherwise. This in turn means that there will be less 'Annual Avoided Variable Costs'. In other words, if SRP invests less in its own solar, then it *will* benefit from avoided generation capacity investment costs, but it will *not* benefit from as many avoided variable costs, because there is now less solar than there would be if SRP had not balanced their investments. This means that they do not avoid as much natural gas plant use as they would have if they had not balanced their investments.

The loop is reinforcing because an increase in rooftop solar will cause SRP to avoid some of its own investments, which (all else equal) reduces their annual avoided variable costs from natural gas plant use. This in turn increases their profit lost, which raises rates, thus leading to greater rooftop solar diffusion.

How does the model represent rooftop solar's effect on CO_2 emissions?

As seen in figure 6 below, the model uses the variable of the 'Additional MWhs produced from Solar due to Rooftop Solar Diffusion' to determine not only the variable costs avoided due to rooftop solar, but also the additional CO_2 emissions prevented by rooftop solar. These additional MWhs displace production from natural gas plant generation, and so for every additional MWh produced in the rooftop solar diffusion case, we can say that a certain amount of CO_2emissions (determined by the 'CO_2 Emissions per MWh produced by Natural Gas Plants') were prevented due to rooftop solar difusion.

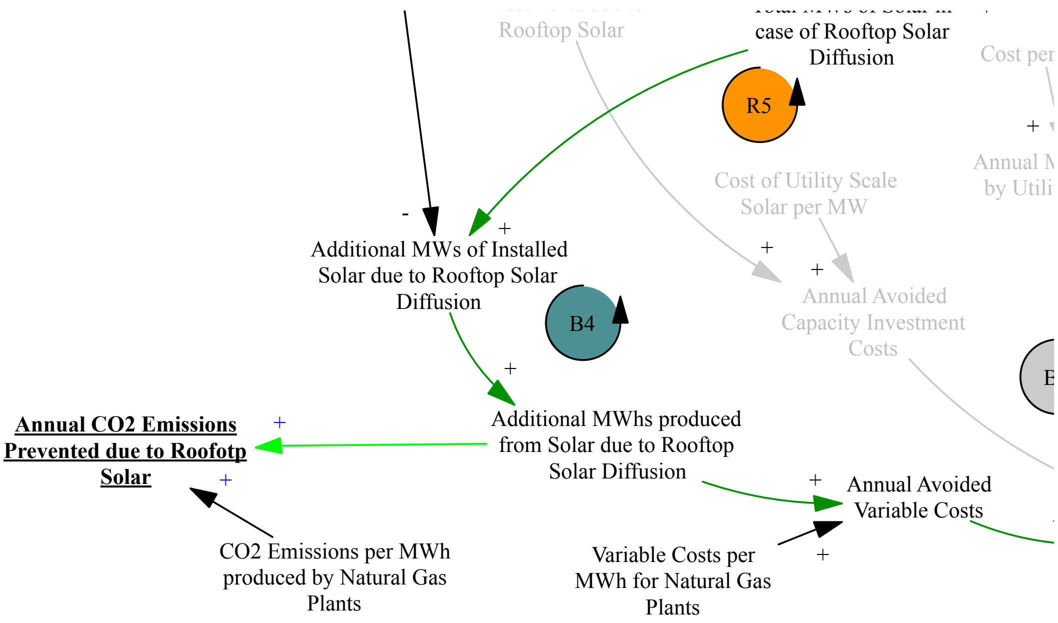

Figure 6 - CLD showing how the model represents the CO2 emissions prevented by rooftop solar.

Note that the dynamics determining CO_2 emissions are the same as those determining the avoided variable costs. As such, the additional CO_2 emissions prevented by rooftop solar diffusion is highly dependent on the 'Fraction of Rooftop Solar Installments from which Utility claims RECs'. If the utility *does* claim these RECs, then it *will* balance its investments in its own solar. This means that the total stock of solar in SRP's service area will be smaller, leading to less CO_2 emissions prevented from natural gas plant generation. Converesely, if SRP receives less/none of these RECs, then it will balance less/not balance its investments in its own solar. This leads to a higher stock of total solar, and thus greater CO_2 emissions prevented. However it also means that the utility will not benefit from any avoided generation capacity investment costs, which means that their lost profits and thus addition in rates will be higher. This is the main insight of this CLD – there is a tradeoff between preventing more CO_2 emissions and preventing increases in rates.

Below in figure 7 we see the CLD in its entirety. Note the addition of the 'Special Charge for Solar Customers', which reflects the recent mandatory price plan that SRP introduced for its distributed generation customers. This price plan was said to result in an increase of roughly $50 a month for the average SRP rooftop solar customer [15]. In the model this price plan will reduce the expected savings perceived by potential rooftop solar adopters after the year 2015 (because pre 2015 distributed generation customers were 'grandfathered' from this new rate plan for 20 years [63]). Additionally, the price plan will decrease SRP's annual profit lost due to rooftop solar diffusion (due to the increase revenues).

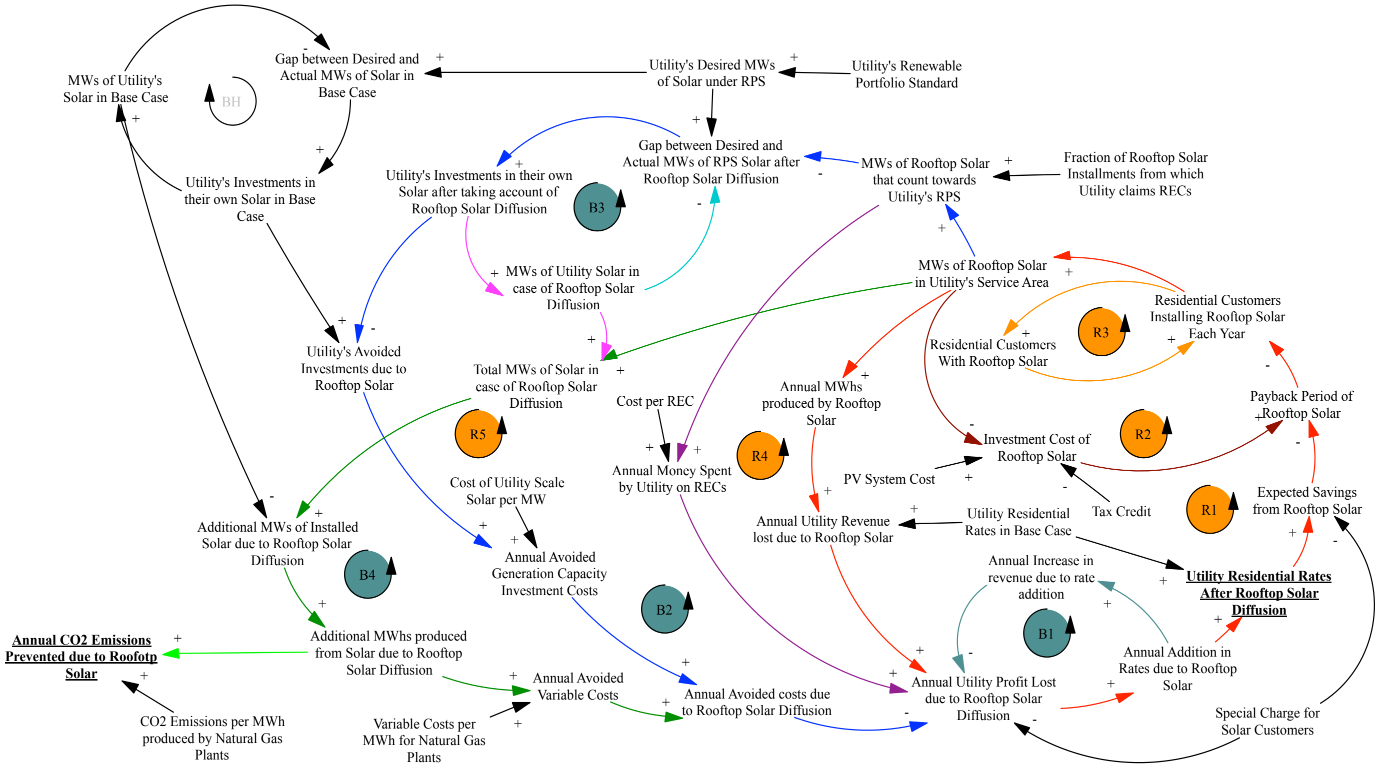

Figure 7 - Whole CLD

What are the Model's boundaries?

Just as every map has an edge, every model must have a boundary. The table below can be used to describe the boundary of this model. It lists the variables in the model which are endogenous (i.e. determined by other variables within the model) and exogenous (i.e. determined by data taken from the perimeter of the model boundary). Issues that are excluded/ignored by the model (outside of the boundary) are also listed.

Endogenous	**Exogenous**	**Excluded**
-SRP customers installing rooftop solar -Annual SRP revenues lost due to rooftop solar -SRP profits lost due to rooftop solar -Addition in SRP's rates	-SRP's Base Case Rates -Overall electricity demand in SRP's service area (including demand that was/will be met by rooftop solar) -Expected annual MWhs produced per MW of	-Change in SRP's grid costs and load losses due to rooftop solar -Effect of battery storage technology on rooftop solar's diffusion and effect on SRP profits -Effect of time-of-use

due to rooftop solar -Expected savings from rooftop solar -Overall perceived installed cost per MW of rooftop solar (affected by the stock of rooftop solar in SRP's service area) -SRP's own stock of solar after the effects of rooftop solar -Annual SRP capacity investment costs avoided due to rooftop solar -Annual SRP variable costs avoided due to SRP solar -CO_2 emissions prevented due to rooftop solar	solar in Arizona -Growth rate of Arizona's electric customers -Time to install rooftop solar -Adoption from WOM fraction -Contact rate (between solar adopters and non-adopters) -Average MWs installed per rooftop solar adopter -Historical and projected cost per MW of installed residential solar -Historical and projected cost per MW of utility scale solar. -Years between rooftop solar installation and receiving contract for RECs -Price of RECs to claim 1MWh worth of solar output	plans on SRP's profits lost due to rooftop solar -Effects of rooftop solar on the economy in general (jobs created) -Effects of SRP's lost profits on its ROE[xii] and shareholder earnings[xiii] -Effects of SRP's lost profits on the rating of their bonds -Effects of addition in rates on social inequality among SRP's customers -Effects of rooftop solar policies on SRP's public relations -How rooftop solar diffusion could be affected by a shortage of supply for PV systems and/or rooftop solar installation companies.

[xii] Note that if ROE goes down due to SRP's lost profits, SRP's investors may deem their investment more risky and thus demand a higher return. This in turn will have a negative effect on SRP's profits, resulting in another vicious loop between lost profits and demands for higher return from investors. This loop is ignored in the model.

[xiii] In one study, shareholder earnings is said to be more affected by rooftop solar diffusion than both return on equity and utility rates. This is because of 'deferred capital expenditures that would otherwise generate earnings for shareholders' (page ix of reference [6]).

	-SRP’s solar renewable portfolio standard for each year -Variable costs per MWh of natural gas plant use -Million tons of CO_2 emissions per MWh of natural gas plant generation	

What assumptions does the model make?

System dynamics models are highly aggregated and highly simplified representations of reality. As such they are often built upon many assumptions. Such assumptions can be necessary/justifiable based on either (i) the need for simplicity and/or (ii) the lack of available data. The list below describes and justifies the assumptions upon which this model was based:

1. Regarding avoided generation capacity investments; I assume that rooftop solar can only allow SRP to forego investments in its own solar, and not in any of its other types of generation technologies. This assumption is based on the fact that, for reasons of security of supply, it is said to be difficult to determine the extent to which presence of solar capacity can allow utilities to reduce their investments in dispatchable generation technologies such a natural gas or coal plants [64]. This is because the sun may not be shining at the times of peak demand, and so in order to ensure that such demands could be met at all times, utilities would require the same/a similar size stock of dispatchable technologies as they would if there was no solar capacity. Thus for simplicity we assume that rooftop solar can only allow utilities to avoid investments in their own solar, and not in their dispatchable generation technologies.

2. I assume that the only way in which rooftop solar can allow SRP to forego investments in its own solar is if it receives renewable energy certificates for the output of some/all of the privately owned systems.

3. SRP's RPS (which as a public utility is not legally binding) is to meet 20% of its expected demand in 2020 by renewable resources [65]. The goal beyond 2020 has not been stated yet but in the model I make a simple

assumption that the goal will be increased to meeting 40% of the demand by renewables by 2030. I assume that SRP wishes to produce half of this renewably generated electricity through solar technology. Thus I assume that the goal for 2020 will be to meet 10% of demand through solar, and by 2030 it will be to meet 20% of demand through solar technology. Changing these assumptions has little effect on the important model variables.

4. I also assume that SRP plan to meet these goals for the years 2020 and 2030 via a number of goals for each year, and that the goals for each year will increase exponentially or linearly (depending on the scenario set by the model user). The justification for this is that solar prices are falling rapidly, and so I presume that SRP will want to make increasing investments as time passes, rather than making the most investments at the beginning of the simulation period, when solar prices are highest.

5. I assume that this goal of meeting a certain percentage of expected demand (i.e. a certain number of MWhs) through solar technology translates into a certain desired level of MWs of solar, in order to be able to produce the necessary MWhs.

6. I assume, for the sake of simplicity, that the only way that SRP can claim RECs from its customers' rooftop solar systems is by buying them. It has also been said that utilities may also claim the RECs from such a system if they provided an incentive for the customer to install the system [66]. This possibility has been ignored in the model because its effect is essentially the same as the utility buying these RECs (i.e. instead of buying the REC, the utility gives an incentive).

7. I assume that in SRP's RPS, it is responsible to meet a certain percentage of total customer demand *minus* the demand that comes from rooftop solar systems from which SRP are *not* claiming RECs. This assumption seems reasonable, seeing as the demand met by such rooftop systems does not come from SRP's generation. However if SRP does claim the RECs from the output of some of these systems, then it can be assumed that this will increase the total MWhs of demand for which they are responsible, seeing as the output of such systems could be considered as SRP's own generation in some sense.

8. I assume that when SRP obtains RECs from rooftop solar, it does so by entering into a contract with the rooftop solar owner. The model also assumes that this contract will last the whole lifetime of the rooftop solar

system, and that the price paid for these RECs is not fixed but can vary year to year (depending on the price of RECs set by the model user).

9. I assume that SRP will make their investments in their own solar generation technology with lump sums paid over 1 year.

10. I assume the costs avoided due to rooftop solar increase linearly with greater rooftop solar penetration of the market. Other studies have shown that as the presence of distributed solar resources increases in a market, the costs avoided on behalf of these solar resources does not increase proportionately, but disproportionately [6]. In other words, rooftop solar brings results less and less costs avoided per MW as its presence in the market grows. However, for the sake of simplicity in the model, this dynamic has been ignored.

11. Regarding avoided variable costs, I assume that rooftop solar output allows for avoided variable costs that would have arisen from natural gas plant use only. This is justified by the fact that solar energy usually only displaces use of Natural Gas plants, and not of other generation technologies [50]. This is because Natural Gas plants have the ability to quickly ramp up and down their output, and so can more easily be used in conjunction with the intermittent output of solar than it can with the less agile output of Coal or Nuclear plants. Additionally, in Arizona peak demand happens at the sunniest times of day (largely due to air conditioning use) [67], and at peak times such as these Natural Gas plants are being used to meet the quick spike in demand. Thus because this peak demand happens at the sunniest times of day, when solar output is greatest, I can increase the confidence in our assumption that solar output generally replaces Natural Gas plant output. As such, any increase in solar energy will likely decrease the use of natural gas plants only, and not of the other kinds of plants, such as Coal or Nuclear.

12. I assume that the addition in rates due to rooftop solar diffusion will be calculated by dividing 'SRP's profit lost' by the expected annual kWhs of demand from residential customers. That these lost profits are made up for from residential customers only is not a certainty but a necessary assumption based on lack of information on how exactly SRP's lost profit from rooftop solar diffusion would affect their rates. However, according to APS, Arizona's largest utility, all residential and small business customers are subject to a 'lost fixed cost recovery' charge, which is partly determined by lost profits due to rooftop solar diffusion [36]. APS note that large commercial and industrial customers have current rate structures which already include the recovery of fixed costs, and so are

exempt of this charge [36]. Thus I take this to mean that the lost profits (or gains made) due to rooftop in the case of SRP will also be spread over the demand of the residential/small-business sector only.

13. Information on the exact number of residential customers that SRP has could not be found. However data on the fraction of demand that comes from residential customers in the state of Arizona as a whole could be found [68], and this was used to estimate the fraction of demand that came from SRP's residential customers.

14. The lifetime of rooftop solar systems is assumed to be 25 years. Some studies estimate this lifetime to be 30 years [69], whilst others use an estimate of 20 years [70]. As such, the average value of these studies was used.

How does the stock and flow diagram represent the effect of rooftop solar on SRP's revenues?

The stock and flow diagram (SFD) of the 'lost revenues' part of the model is presented in figure 8 on the next page. Blue coloured variables are those caught in loops. Red variables denote policy parameters, green variables denote scenario variables, whilst black variables denote parameters whose value is more or less set in stone. The term rooftop solar is sometimes abbreviated to RS when necessary.

We can begin our explanation of the SFD with the stock of potential rooftop solar adopters, which represents the number of SRP's residential customers whose residence has the necessary characteristics for installing rooftop solar panels. The data for the year 2000 could not be found and so an approximation was made for the initial stock value (see appendix B). The model assumes that this stock changes at the same rate that all of Arizona's electric customers has been changing and is expected to change in the future.

From the stock of Potential Rooftop Solar Adopters, a certain number will install rooftop solar systems each year, which fills the stock of rooftop solar adopters. This flow also affects the stock (MWs) of rooftop solar present in SRP's service area, based on an average size of 4.5kWs for residential solar systems [71]. Note that there are no outflows for these stocks, based on the fact that in all scenarios almost no solar capacity gets added before 2005. Since solar capacity is assumed to last for 25 years in the model, then hardly any of the capacity in the model would actually depreciate between 2005 and the end of the simulation period (the year 2030).

Each of these MWs will then produce 1730 MWhs per year in Arizona, according the PVWatts calculator of the National Renewable Energy Laboratory [72].

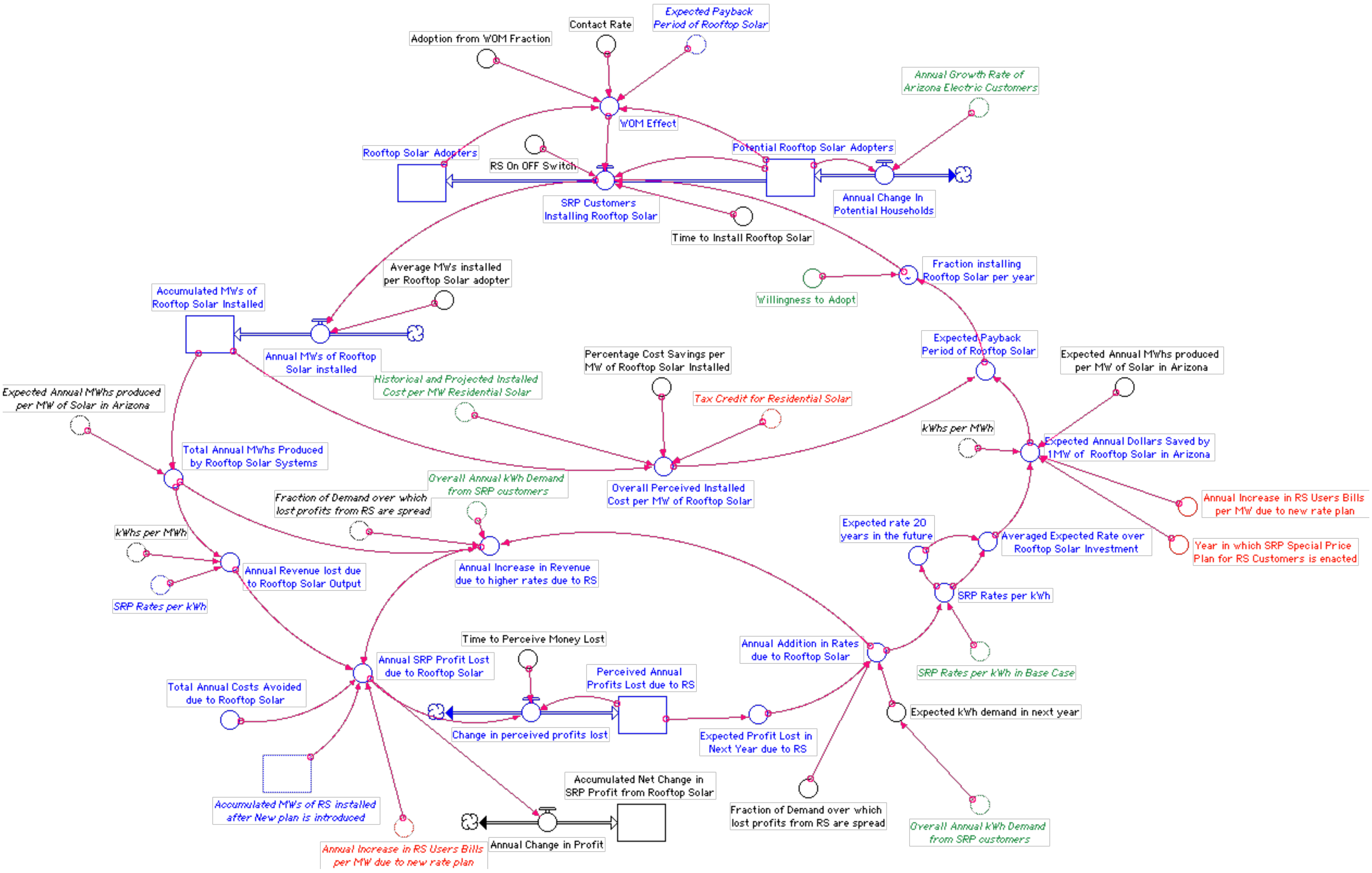

Figure 8 - SFD representing loops R1, R2, R3, and B1

These MWhs will then replace those that would otherwise have been bought from the utility. Therefore, in the model each MWh from rooftop solar will reduce SRP’s revenues. Note that because of the policy of 'Net metering', we can assume that all MWhs produced by these rooftop solar panels will reduce SRP’s revenues in the same way. This is because net metering allows rooftop solar customers to export their excess electricity (i.e. the electricity that is being produced by their panels at a certain moment but not being used by them at that moment) to the grid in return for 'credits' on their monthly bills from the utility. In Arizona and in most U.S. states, these credits are equal to the retail price of electricity [12]. As such, any MWh produced by these panels, whether used by the customer or exported to the grid, will reduce the utility's revenues by the same amount (i.e. by the retail price).

Also note that in the model we calculate the revenue lost using the 'SRP Rates per kWh in Base Case' (i.e. the Rates for SRP's residential customers in the case of no rooftop solar diffusion). The rates from the Base Case are used in the model so that we do not double count the lost revenues resulting from rooftop solar diffusion. For example, if we used SRP's rate *after* rooftop solar diffusion, and if this rate was 5% higher than the base case, then SRP's lost revenues would appear 5% higher than they actually should. As such the Base Case Rates are used to calculate the lost revenues. Nonetheless model users should note that the fallacy of double counting the lost revenues may actually happen in reality, as SRP may falsely use their actual rates to determine their lost revenues from rooftop solar, even if these rates have already been increased/decreased due to rooftop solar. However in this model we assume that lost revenues will be calculated properly by SRP.

SRP's annual lost revenues then increase the 'Annual SRP profit Lost due to Rooftop Solar'. These lost profits are also increased by the money that SRP spends on RECs each year. Conversely, SRP's annual profit lost is decreased by (i) the costs avoided as a result of rooftop solar, as well as any extra revenues gained due to rooftop solar, which includes (ii) revenue from higher-than-otherwise rates (which increases revenues from all demand except that which is met by rooftop solar) and (iii) increased revenues from all customers who take on the new rate plan for SRP rooftop solar customers. This

After a 1-year information delay to perceive these lost profits (represented by the stock and flow structure), the model then assumes that SRP's board of directors will make a projection about how much profit they expect to lose (as a result of rooftop solar) in the next year. The equation representing this projection is as follows:

```
Perceived_Annual_Profits_Lost_due_to_RS+SMTH1(Perceived_Annual_Profits_Lost_due_to_RS*TREND(Perceived_Annual_Profits_Lost_due_to_RS,3.5,0),5,0)
```

The trend function represents the rate of change of the input variable, i.e. the Perceived Annual Profits Lost. It is assumed that this projection is based on an analysis of the trend of SRP's profit change over the past 3.5 years. In the model, 3.5 years has been chosen as the averaging time for all built-in equations that are directly related to perceiving and/or changing SRP's rates. This is because most U.S. electric utilities are said to hold rate cases (whereby they update their rate plans) every two to five years [16], meaning every 3.5 years on average. In this equation the SMOOTH function was used to correct some unrealistic behaviour in the output of the TREND function.

Due to the 'cost recovery' way in which SRP set their rates (see Chapter 2 for more on this), these expected lost profits are then used to determine the 'Addition in Rates due to Rooftop Solar', whose equation is as follows:

SMTH1(Expected_Profit_Lost_in_Next_Year_due_to_RS/(Expected_kWh_demand_in_next_year*Fraction_of_Demand_over_which_lost_profits_from_RS_are_spread),3.5,0)

The SMOOTH function here is used to represent the fact that SRP has a 'pricing principle' known as *Gradualism* whereby price levels are stabilized and the impacts of cost movements are smoothed, so as to provide their customers with more stable rates [20]. Again the averaging time is 3.5 years because this is the average time over which rate decisions are based. The input to this smooth function is the expected profit lost divided by the demand that is expected to come from SRP's residential customers (it is divided by the demand from *residential* customers, based on assumption 12 on page 27).

As already discussed Chapter 2, rates are set under cost recovery by dividing the expected cost of providing service by the expected demand for electricity [16]. This partly explains why profits lost are being divided by a certain amount of the demand in the model. However it should be noted that in the model we are essentially treating the lost revenues as if it were a cost, because it increases the top of this fraction (which is usually cost of service), rather than decreasing the bottom (which is the demand, i.e. what is actually being reduced by rooftop solar). The reason we model it this way is because it allows us to avoid having to model all of SRP's costs of providing service, the data for which could not be found. Instead, we simply find how much profit was lost due to rooftop solar, determine how this lost profit will affect the rates, and then add this effect to the exogenously determined data of the Base Case SRP rates[xiv] (i.e. the rates in the case of no rooftop solar diffusion). In this way we are essentially treating lost profits as if it were a cost.

This avoidance of modeling SRP's costs helps us to better isolate the 'death spiral' hypothesis, by keeping our focus on the dynamics (and rate changes) that come about as a result of rooftop solar diffusion alone, and not on the myriad of other unrelated factors that affect how SRP's rates are set (which ranges from grid costs to fuel costs to capacity investment costs). In any case, the model user could test the effects of rising costs unrelated to rooftop solar diffusion by setting a higher growth rate for SRP's Base Case rate, as rising rates would reflect the effects that rising utility costs (without a sufficient rise in demand) would cause.

[xiv] Note that there is not one rate for SRP's residential customers, but rather several rate plans from which SRP's customers can choose based on their needs. However for the sake of simplicity, the model uses data from the average residential rate in Arizona, ignoring the difference in rates brought about by different rate plans.

Note that because historical rates (available until 2013) will have already included the effects of rooftop solar diffusion, we do not add this effect to rates until after 2013. Otherwise we would be double counting the effects of rooftop solar diffusion. Thus the equation for SRP's rates per kWh after rooftop solar is:

IF TIME > 2013 THEN SRP_Rates_per_kWh_in_Base_Case + Annual_Addition_in_Rates_due_to_Rooftop_Solar ELSE SRP_Rates_per_kWh_in_Base_Case

The next variables in this loop (R1 in the CLD) represent customers' expectations about the profitability of investing in a rooftop solar system, based on SRP's rates. Survey evidence has shown that the economic attractiveness of rooftop solar systems is an important factor in determining their adoption rate [14]. It has also been suggested that a payback period is the financial metric most commonly used by potential rooftop solar adopters [71,73], and for this reason it has been chosen as the financial metric used in this model.

In determining this payback period, potential rooftop solar adopters would look at SRP's current rates, as well as make projections about what the rates would be in the future. This is so that they could estimate the rate that they would be avoiding by investing in a rooftop solar system. This in turn would tell them the savings that such an investment would bring. In the model we determine these expected savings by first representing the 'Average Expected Rate over Rooftop Solar Investment', which is calculated as follows:

(Expected_rate_20_years_in_the_future+SRP_Rates_per_kWh_after_Rooftop_Solar)/2

This is based on the assumption that the potential adopter will make a projection about the rate in 20 years time[xv], and will expect the rate to change in a relatively linear fashion between now and then. So if the current rate was $.11/kWh, and the projected rate in 20 years was $.21/kWh, then we imagine that the potential adopter would perceive the average rate over the 20 year period to be .11+.21/2 = $.16/kWh.

Thus the equation to represent the expected rate 20 years in the future is as follows:

SRP_Rates_per_kWh_after_Rooftop_Solar+ SRP_Rates_per_kWh_after_Rooftop_Solar*20*TREND(SRP_Rates_per_kWh_after_Rooftop_Solar,5,.02)

It is assumed that the potential adopter makes a projection based on the behaviour of the rates over the previous 5 years. This TREND function is

---

[xv] 20 years has been reported as the time period over which most SRP customers base their investment decisions regarding rooftop solar [25].

multiplied by 20 because the trend function by itself only allows for a projection of just one time step into the future, which in this model is just one year, whilst we are representing someone looking 20 years ahead. Also note that the TREND function was initiated as .02, to represent the fact that potential adopters in the year 2000 (the first year of simulation) would have been making projections based on years previous to the simulation period. Calibration showed that .02 was the most likely perceived trend at that time.

Given this expected average rate, and given the output per MW of solar in Arizona, we can determine how many dollars one could save each year by investing in a MW of rooftop solar. For all those customers looking to adopt rooftop solar after the new rate plan has been introduced (in 2015), these expected savings will be reduced by $150000 per year per MW, which is about $600 per year for the average 4kW system.

These expected savings then help us to determine the expected payback period for solar, whose equation is:

Overall_Perceived_Installed_Cost_per_MW_of_Rooftop_Solar/Expected_Annual_Dollars_Saved_by_1MW_of__Rooftop_Solar_in_Arizona

The Overall Perceived Installed Cost per MW is determined by the exogenous data of the historical and projected installed cost per MW of rooftop solar, and is reduced by the tax credit, as well as any savings due to increased experience, i.e. the 'Percentage Cost Savings per MW installed' multiplied by the stock of MWs installed.

Based on the payback period, a certain fraction of the Potential Rooftop Solar Adopters will install rooftop solar systems each year. This fraction is determined by a graphical function. This graphical function (seen in figure 9 on the next page) was formed by calibration against the one available data point (for 2015) for the number of SRP customers who had installed rooftop solar in SRP's service area, which revealed that SRP had 15,000 rooftop solar customers at the beginning of 2015 [25]. As such the graphical function was formed so that the stock of Rooftop Solar Adopters would be 15,000 in 2015. Determining how rooftop solar's payback period affects its adoption rate is difficult, and to this author's knowledge other rooftop solar diffusion studies also use calibration against real data to determine this relationship [60,71]. The way in which this stock was filled previous to 2015 is uncertain due to lack of data, and so an estimation was made. However, the shape of the graphical function was informed by the shape of similar graphical functions revealed in another study [71].

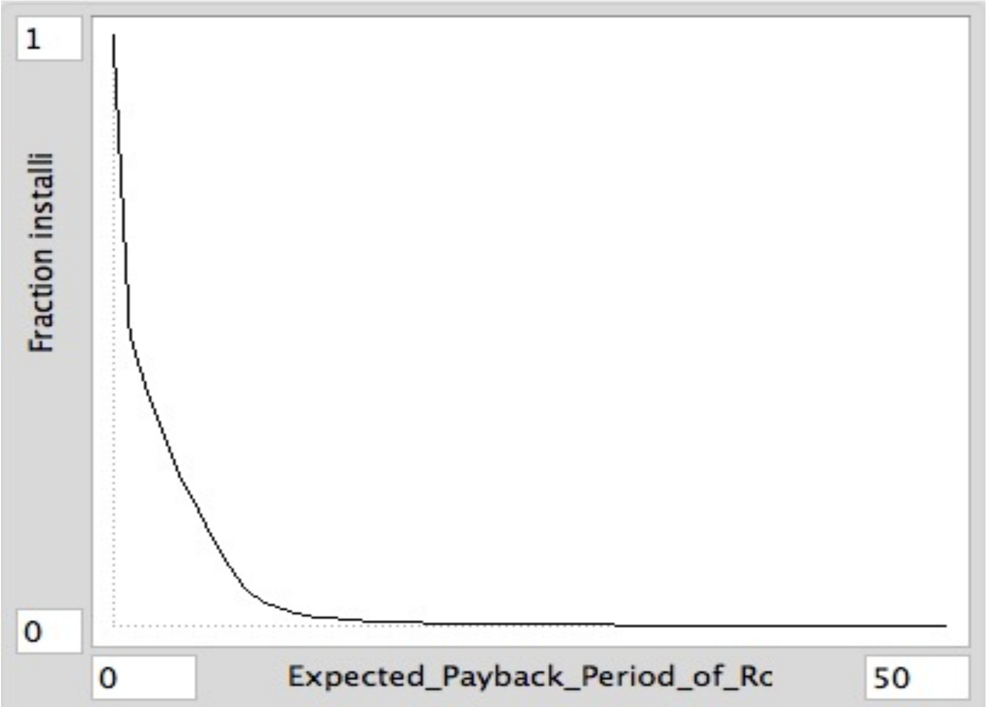

Figure 9 - the graphical function used to determine how rooftop solar's payback period will affect the fraction of potential adopters installing rooftop solar each year.

In the model the adoption fraction can be easily changed via the 'willingness to adopt' variable, whose default value is 1. Increasing this variable will increase the adoption rate, whilst decreasing it will have the opposite effect.

Additionally, the fraction adopting is also affected by a 'word-of-mouth' effect. This effect represents the fact that rooftop solar adopters will spread the word about their investment to their friends, family, and neighbors (via a 'contact rate'), some of whom (the 'adoption from WOM fraction') will then go on to become adopters themselves. Such an effect is often included in models looking to replicate the diffusion of a relatively new technology [14,60,61,74]. The fraction of innovators (those who adopt the new technology first, without relying on the word-of-mouth effect) in this model is represented in the graphical function, which has a .1 percent adoption rate even when the payback period is between 25 and 30 years. Payback periods longer than 30 years have been shown to have no adoption rate for rooftop solar [71].

The equation for the word of mouth effect is as follows:

```
IF Expected_Payback_Period_of_Rooftop_Solar <30 THEN
(Potential_Rooftop_Solar_Adopters*Rooftop_Solar_Adopters*Contact_Rate*Adoption_from_WOM
_Fraction)/(Potential_Rooftop_Solar_Adopters+Rooftop_Solar_Adopters) ELSE 0
```

This word of mouth effect will only exist when the payback period is below 30 because, as already stated, payback periods greater than this have been shown to result in no rooftop solar diffusion [71]. The contact rate of this equation represents the number of 'meetings' per year that each solar adopter would have with a potential solar adopter. A certain fraction of these meetings (the adoption from WOM fraction) will result in the potential adopter becoming an actual adopter. The structure of this equation has been informed by literature from Frank Bass[61] and John Sterman[54].

I have now presented the part of the stock and flow model that represents both rooftop solar diffusion and how this affects SRP's revenues, which in turn affects its rates. We can now look at how the stock and flow model represents SRP's avoided costs as a result of rooftop solar.

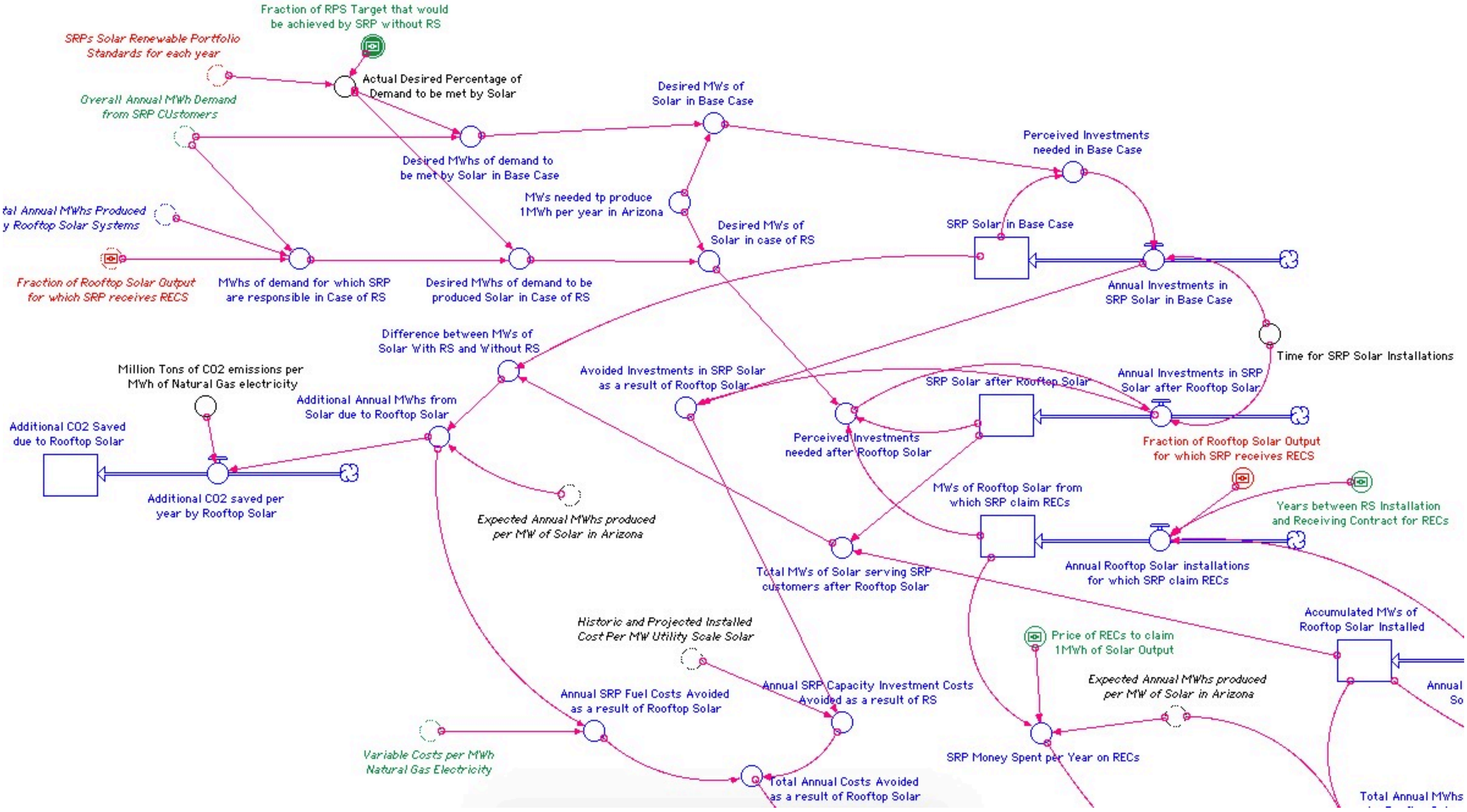

Figure 10 - SFD of the avoided costs part of the model.

To begin the explanation of this section, it helps to start in the top left corner, with the variable 'SRP's Solar Renewable Portfolio Standards for each year' which was explained in the CLD section. To get the 'Actual Desired Percentage of Demand to be met by Solar' we multiply this variable by the 'Fraction of RPS that would be achieved by SRP without RS'. This latter variable was included so that model users could test the effects of their assumptions regarding SRP's ability to actually succeed in their RPS goals. Model users may feel that SRP would have lowered their goals if there was less rooftop solar diffusion, and they may feel that this in turn would have an effect on how much rooftop solar affects SRP's avoided costs, as well as the prevention of CO_2 emissions. Including this variable in the model allows users to test the effects of these assumptions.

From the desired percentage of demand to be met by solar we can determine the desired MWhs to be produced by solar, given the demand (historical and expected) for SRP's electricity. Note that there is a different desired MWhs of demand to be met by Solar in the Base Case than in the RS case (i.e. in the case of rooftop solar diffusion). This is because in the case of rooftop solar diffusion, I assume that SRP will *not* have to meet that demand which is met by the rooftop solar output for which SRP does *not* receive RECs. I assume that such output can be considered outside of SRP's responsibility, as it is produced by another supplier (the customer) from which they receive no benefits (i.e. neither revenues nor RECs).

Given that 0.579 kWs are needed to produce 1MWh per year in Arizona[xvi], we can then determine SRP's desired level of MWs of solar in both the Base Case and the RS case. Each of these desired levels then determines the 'perceived investments needed' in each case, which in both cases is determined by the difference between the desired level of MWs, and the actual level of MWs (represented as stocks) in each case. The main difference between the two cases is that whilst the Base Case investments needed is affected by SRP's own stock of solar alone, in the RS case the investments needed are also affected (reduced) by that stock of rooftop solar from which SRP can claim/buy RECs. As such if SRP do claim RECs from these systems, then their investments in their own solar in the RS case are likely to be less than in the Base Case.

By finding the difference between the investments in the Base Case and the RS case, we can determine the 'Avoided Investments in SRP solar due to Rooftop Solar'. This variable then helps us to determine SRP's annual avoided generation capacity investment costs, given that they are no longer investing in a certain number of MWs of their own utility scale solar.

As regards avoided variable costs, the model calculates this based on the difference between the stocks (rather than the flows) in each case. This difference between the stocks in each case (i.e. the Base Case and the RS case) tells us how many 'additional' (or 'incremental') MWhs were produced due to rooftop solar diffusion. Based on assumption 11, this can then tell us how many

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[xvi] This calculation is based on the fact that 1MW will produce 1730 MWhs per year in Arizona, according to the PV watts calculator [72]

MWhs of natural gas plant generation were avoided by SRP. Given certain variable costs per MWh of natural gas plant generation, we can then determine SRP's avoided variable costs due to rooftop solar. Adding this with the avoided capacity investment costs, we can determine the 'Total Annual Costs avoided due to Rooftop Solar'. This will then go on to reduce the 'Annual SRP Profit lost due to Rooftop Solar'.

Additionally, in this section of the model we see how the 'SRP money spent on RECs' variable (which will increase profits lost) is calculated based on a multiplication of the stock of rooftop solar from which SRP claims RECs, by the annual MWhs per MW in Arizona, by the price for 1MWh worth of RECs.

Finally, the 'Additional Annual MWhs from Solar due to Rooftop Solar' variable also helps us to determine the additional CO_2 emissions prevented due to rooftop solar. Multiplying the former variable by the CO_2 emissions per MWh of natural gas generation can give us the annual flow of CO_2 emissions saved solely due to rooftop solar. These annual CO_2 emissions prevented can then be accumulated in a stock, to give the model user an idea of the total CO_2 emissions prevented due to rooftop solar diffusion.

That concludes the description of the model. Before we look at the model's behaviour and its reaction to different policies, we should first determine how much confidence should be placed in the model and its simulation results. As such the next chapter will be devoted to model validation.

6. Model Validation

How do we know if the model is a sufficiently accurate representation of reality, and how much trust can we have in the insights that it provokes?

To answer the first question above, we must perform some validation tests on the model. This in turn will tell us how much certainty/uncertainty there is the model, which should inform the level of trust we place in the model's insights.

Validating a system dynamics model has been described as a gradual process of establishing confidence in the soundness and usefulness of a model [75]. The usefulness of the model depends on its purpose, and so it has been argued that model validity should be judged in light of the model's purpose [76]. As such the validity of this model will be determined based on its ability to determine the effect of rooftop solar diffusion on SRP's rates and CO_2 emissions.

In validating the model, we must evaluate both its structure (i.e. the qualitative cause and effect relationships that it represents) and its behaviour (i.e. the quantitative simulation results that it produces) [77]. It is better that we begin with the structural validation, as doing so allows us to know that if we do get the right behaviour, it will be for the right reasons [77]. In carrying out the validation of this model, I have followed the guidelines laid out by Barlas (1996), which recommends the following three groups of validation tests:

1. Direct structure tests
2. Structure –oriented behaviour tests
3. Behaviour pattern tests

1. Direct Structure Tests: Is the model's structure qualitatively valid?

<u>A - Structure Confirmation Test:</u> All cause and effect relationships in the model have been based on the literature referred to in the previous chapters. As such, the validation approach here could be said to be theoretical, as no interviews were carried out with SRP managers in order to confirm any of the model's structure. Therefore it should be noted that some of the models cause and effect relationships were based on generalisations that may not accurately reflect SRP's own mode of operation. Nonetheless, documents relating particularly to SRP were used whenever possible. However, to truly verify the structure of the relationships in this model, interviews would need to be held with the relevant managers from SRP.

Perhaps the most uncertain causal relationships in the model are those relating to the RECs arising from rooftop solar systems. This is due to a lack of clear literature on this subject in the U.S. [66]. Despite online research and numerous phone calls to SRP representatives, I was unable to get a clear answer as to whether or not SRP purchases or claims the RECs from their customers' rooftop solar systems. Out of about ten separate calls, eight agents (some from the solar department) told me that they did not know whether SRP ever purchased these RECs. From the two agents that did give me an answer, the information was slightly conflicting – one told me that SRP used to receive these RECs, when they offered incentives for the customer to install the rooftop solar system. This agent told me that since SRP has recently stopped providing these incentives, they no longer receive these RECs. The other agent told me that SRP could choose to buy these RECs if they want to, yet information on the price of these RECs was unavailable. Regarding other U.S. electric utilities, some information was available which revealed that there is quite different treatment of RECs from different utilities [66]. For example, some U.S. electric utilities are legally obligated to meet a certain percentage of their RPS through distributed generation resources [66].

One other uncertain causal relationship in the model is the relationship between SRP's profits lost due to rooftop solar, and the resulting addition/subtraction in SRP's rates. I was unable to obtain detailed enough information from SRP to determine exactly how these lost profits might affect their rates. However, publications on U.S. electric utilities' ratemaking process did shed some light on this matter [16]. Additionally, I was able to see from APS's 'lost fixed cost recovery' charge that the lost revenues resulting from rooftop solar were gathered through an addition to their 'normal' rate, and that this addition applied only to residential and small-scale business customers [36]. As such I assumed this would also be the case for SRP. However model users should note that SRP might in fact have a different way of coping with their lost profits from rooftop solar.

B - Parameter Confirmation Test: All parameters in the model were obtained from literature. The values of some parameters could not be found directly and so were derived from estimations based on the literature. The most important of these estimations can be seen in Appendix B.

C – Direct Extreme Condition Test: this test assesses the validity of model equations by inputting extreme conditions to the model and assessing the plausibility of the resulting output values against the anticipation of what would happen under a similar condition in real life (Barlas, 1996). So one can ask: what would happen in reality if the government decided to offer a tax credit worth 100% of the price of installing a rooftop solar system? One would expect that in reality the 'Overall Perceived Installed Cost per MW of Rooftop Solar' would drop to zero, as the government is essentially paying for the entire system (via a tax credit). The equation for this variable is:

Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*(1-Tax_Credit_for_Residential_Solar)*(1-Accumulated_MWs_of_Rooftop_Solar_Installed*Percentage_Cost_Savings_per_MW_of_Rooftop_Solar_Installed)

Here we see that if we change the 'Tax credit for residential solar' to 1 (instead of .3) in the model, then this equation will be multiplied by zero (1-1 = 0) and so the perceived installed cost of rooftop solar will indeed be zero, as expected.

D- Dimensional Consistency test: The model's units are consistent, as revealed by the 'Units Consistency Check' function of the iThink software used to build the model.

2. Structure-oriented Behaviour Tests – does the model's structure result in plausible behaviour, i.e. is it quantitatively valid?

In analysing the behaviour of this model, we will use a reference case scenario referred to as Scenario 1. Note that this scenario is different to the Base Case, which refers to the scenario of no rooftop solar diffusion. Instead, Scenario 1 analyses the effects of rooftop solar diffusion, under the following conditions: (i) SRP receive no RECs for their customers' rooftop solar systems, (ii) the tax credit will not be renewed after it expires in 2016, and (iii) SRP's new rate plan and its effect on rooftop solar's payback period and savings will *not* be included in this scenario. This last condition will not be included (even though it has already been introduced by SRP) in Scenario 1 so that it can be more easily evaluated in the policy analysis chapter.

In Scenario 1, all projected growth rates in the model (for example, the growth rate of SRP's Base Case rates) are set under the MEDIUM (rather than HIGH or LOW) scenario, whilst the scenarios for the installed costs of commercial and utility scale solar relative to residential solar are set as NO CHANGE.

A - Extreme Condition Test: this test looks at how the model reacts to inputs of extreme values. The model's output is then compared to the expected (or historical) behaviour that would be (or has been) observed under the conditions of such input values in real life. If the model's output sufficiently matches the expected (or observed) behaviour, then the model passes this test.

A suitable variable for this test is the 'Annual Increase in RS User Bills per MW due to New Rate Plan' variable. An extremely high increase in solar customers' bills would be expected to stop all further rooftop solar diffusion. As seen in figure 11 below, this is indeed what happens in the model - an increase of $1,000,000 (instead of $150,000) per year per MW of rooftop solar implemented in 2015 results in no more rooftop solar diffusion after that time:

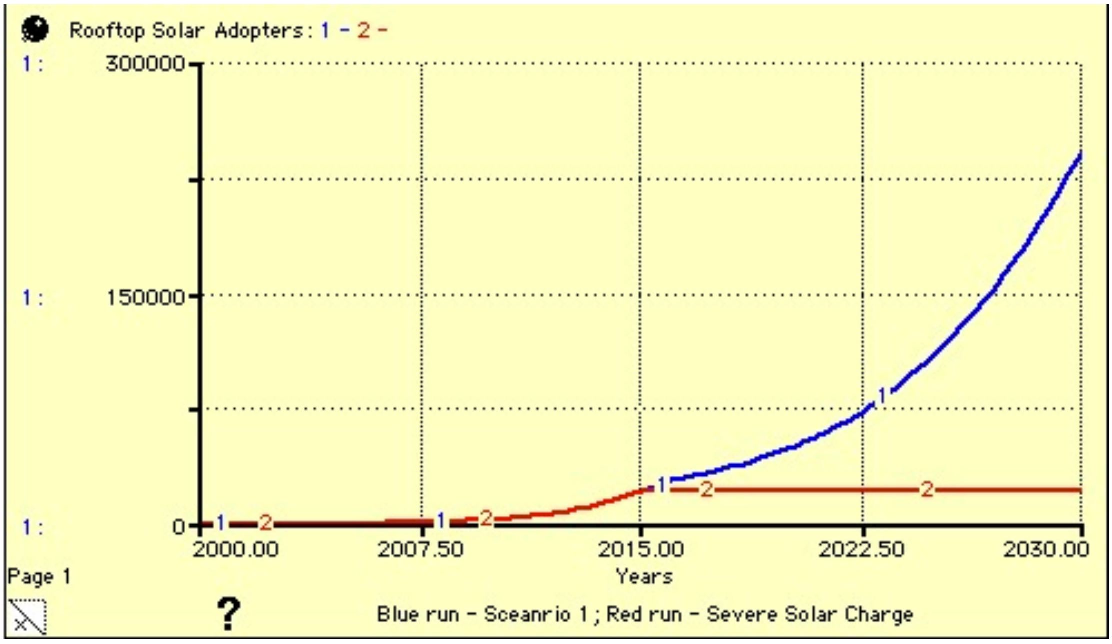


Figure 11 - extreme condition test produces expected results

<u>B – Behaviour Sensitivity Test:</u> these tests look at how the model responds to more realistic variations in its input parameters. If a realistic variation in one of these input variables results in a realistic/expected change in the model's behaviour, then the model is validated by the test. Additionally, such sensitivity tests can tell us about which parameters are highly sensitive in the model. If a realistic variation in the value of a parameter results in a significant change in the model behaviour, then we know that the model is sensitive to this parameter's value. This in turn means that the accuracy of this variable is important for model validity. On the other hand, if a realistic variation of the input variable does *not* produce any significant change in the model's behaviour, then we know that the model is robust towards changes in this input, and the accuracy of this input is of less importance to the model's validity.

Some the most sensitive inputs/graphical functions in the model are as follows:

- Installed price of rooftop solar
- Growth rate in SRP's Base Case rates
- Willingness to adopt

In the sensitivity tests that follow, all simulations will be based on Scenario 1.

Projected Installed price of rooftop solar: The installed price of rooftop solar has dropped significantly in recent years [9], making projections about its future growth quite uncertain (the historic installed costs used in the model are based on reported data, and so can be considered trustworthy enough to be left out of the sensitivity analysis). This variable also plays an important part in the model, as it directly affects rooftop solar diffusion, which in turn affects SRP's rates and CO_2 emissions. To determine its sensitivity, I have used iThink's sensispecs function to produce a number of simulation runs for different values of the annual percentage cost reductions in the projected (i.e. from 2012 onwards) installed cost per MW of residential solar. These different cost reduction rates in the installed cost of residential solar (starting from a common installed cost in 2012) will produce different installed costs over time, with a higher cost reduction rate resulting in lower prices, and a low rate resulting in less cost reductions and thus a higher cost per installed MW. Five different runs are presented, with each run increasing incrementally (by .025) between a 0% annual cost reduction rate (run 1) to a 10% annual cost reduction rate (run 5).

Figure 12 below shows how the five runs produce different costs per installed MW of residential solar (all graphs showing prices use U.S. dollars as units).

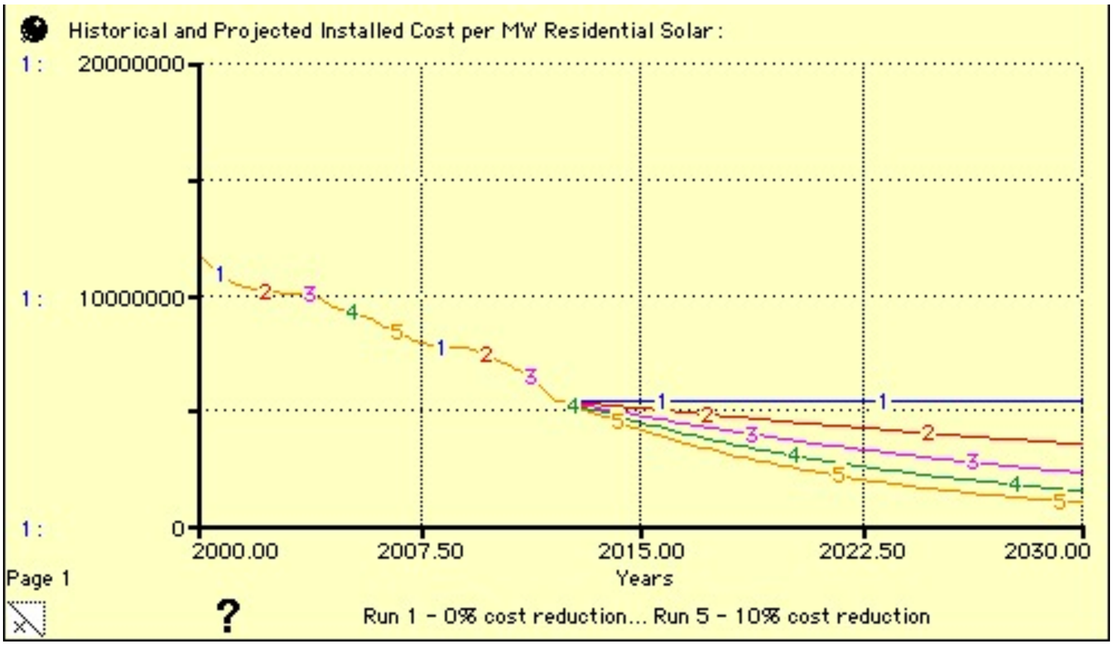


Figure 12 - effects of varying the annual cost reduction rate for residential scale solar; Units are U.S. Dollars

These different installed costs of residential solar then produce the following changes to SRP's rates:

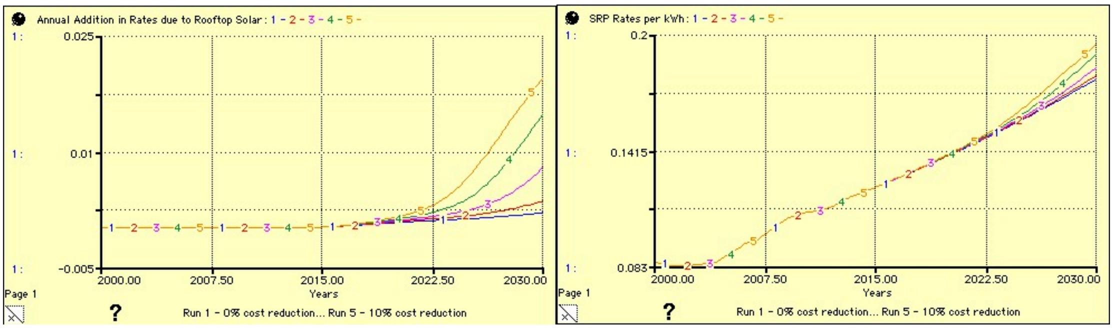


Figure 13 - how SRP's rate is affected by varying the cost reduction rate for residential scale solar

Here we see that even quite an extreme annual cost reduction rate (10% in Run 5) does not have a very extreme effect on SRP's rates. This means that the model is slightly robust to variations and inaccuracies in the projected cost reduction rate for residential scale solar.

As regards CO_2 emissions, the variations in the cost reduction rates produce the following variations in the 'additional' CO_2 emissions due to rooftop solar , which is caused by higher rooftop solar diffusion (note that CO_2 emissions shown in all graphs are measured in millions tons of CO_2):

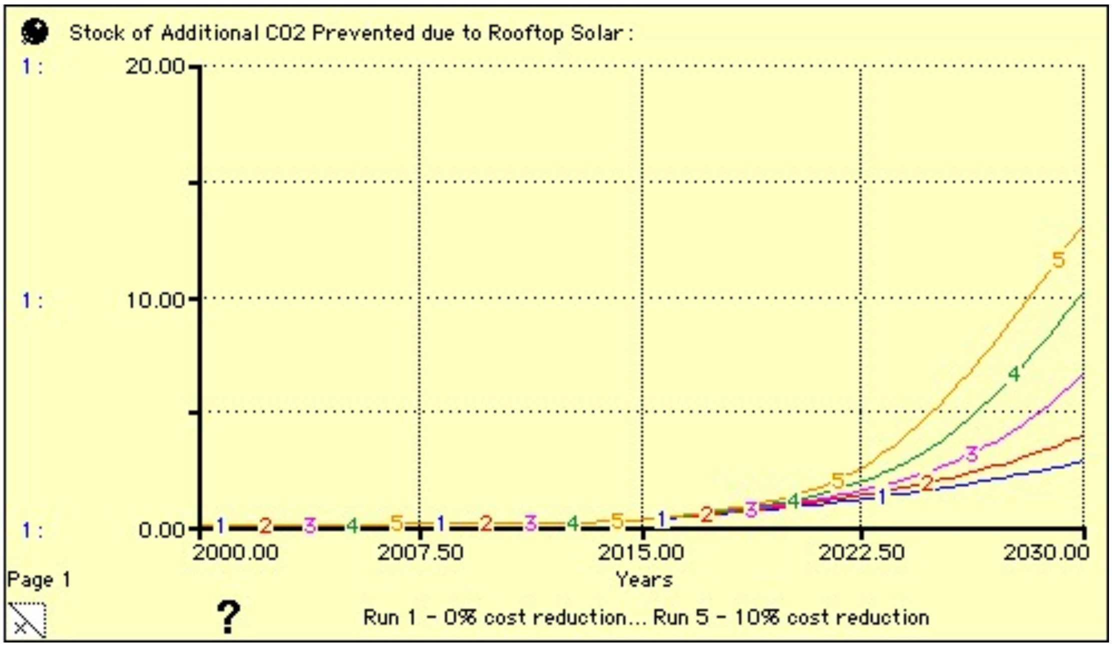


Figure 14 – how CO2 emissions are affected by variations in the cost reduction rate of residential solar

Growth Rate in SRP's Base Case Rates: Utility rates can vary significantly due to the fact that they are dependent on the utility's variable costs. These variable costs are affected by the price of fossil fuels (needed to produce electricity in fossil fuel plants), all of which have been known to vary significantly, and to be particularly hard to predict. SRP's base case rates also play an important role in the model, and so it is important to test the effect of variations in their future value. Again, this is done by testing the effects of different future growth rates (from 2013 onwards) on (i) SRP's rates and (ii) CO_2 emissions.

The graph below reveals the effects of 5 different future growth rates for SRP's Base Case rates, starting with a -2% growth rate per year, increasing incrementally by 2% to the fifth run, which has a growth rate of 6% per year.

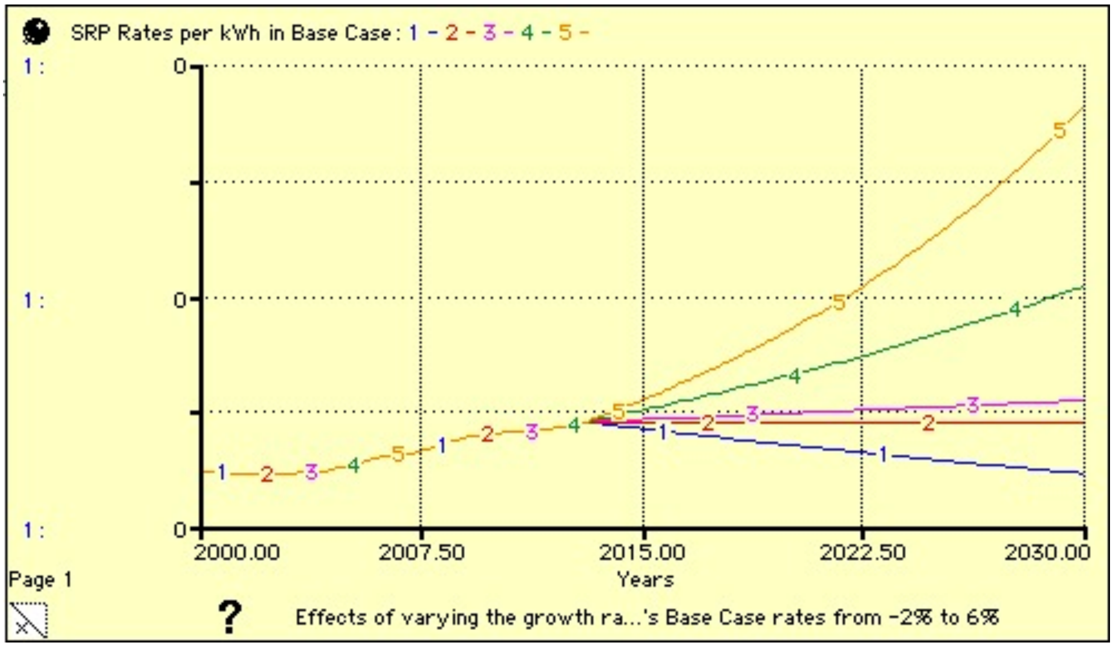


Figure 15 - variations in the annual growth rate of SRP's Base Case Rates

Such input variations have the following effect on SRP's rates after rooftop solar:

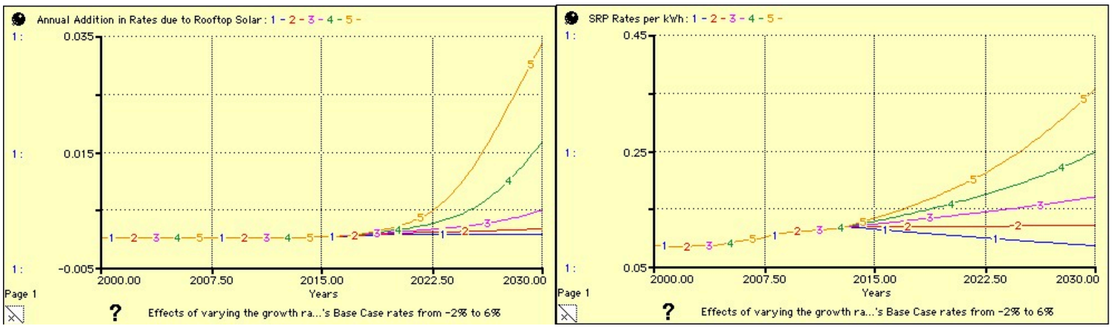


Figure 16 - effect of variations in Base Case rates on the addition in rates due to rooftop solar

Here we see that a variation in the growth rate of SRP's Base Case rates can result in significant changes to the additions in rates. This is because higher Base Case rates result in greater rooftop solar diffusion, which through loop R1 results in even greater additions to the Base Case rates.

This in turn has the following effect on the additional CO_2 emissions prevented due to rooftop solar:

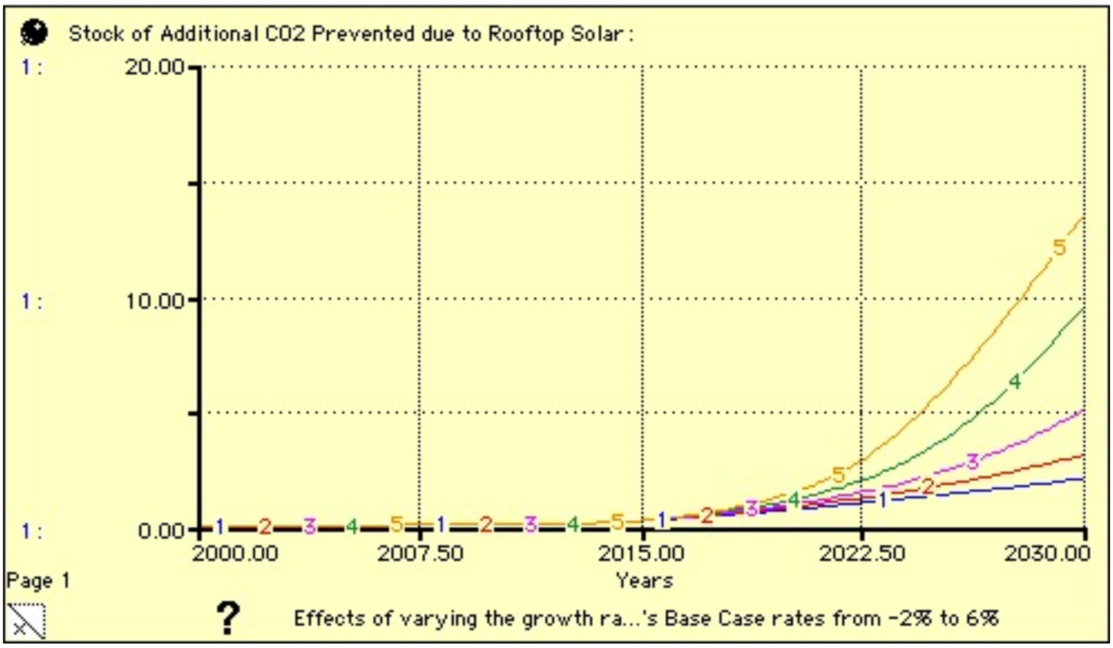


Figure 17 - effects of variation in Base Case rates on the additional CO2 prevented by rooftop solar

By the level of variation seen in these simulation results, we see that the growth rate of SRP's Base Case rates plays quite an important role in the model. If it is low (2% or under) then rooftop solar has little effect on rates. If SRP's rates grow quicker than 2%, however, then there is a more significant diffusion of rooftop solar, and thus more significant addition in rates (and CO_2 emissions prevented).

Willingness to adopt: As discussed in the model description chapter, a graphical function determes how rooftop solar's payback period affects the adoption rate in the model. This graphical function was formed based on calibration against one real data point as well as being informed by the shape of similar graphical functions from other studies [71]. As such there is some uncertainty as to how accurately this graphical function reflects reality. By varying the willingness to adopt variable, we can determine how increasing or decreasing this adoption fraction will affect the model. The graph below shows results (for SRP's rates and CO_2 emissions) from 5 runs, increasing incrementally (by .25) from a willingness to adopt of .5 (i.e. the adoption fraction will be half of what it normally is) in run one to a willingness to adopt of 1.5 in run five.

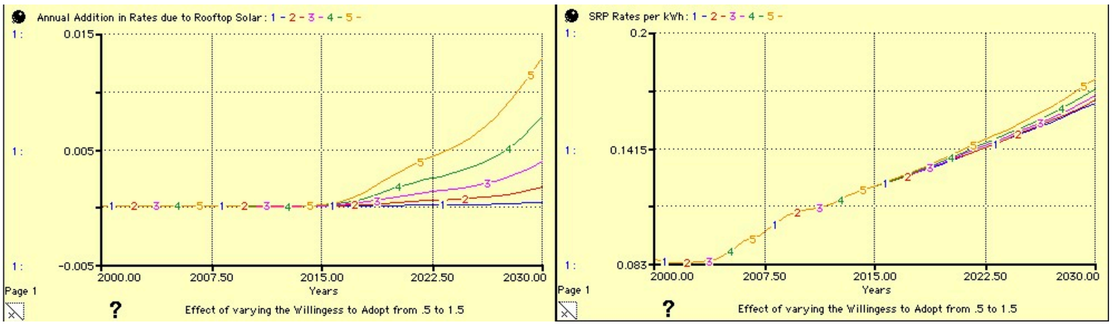
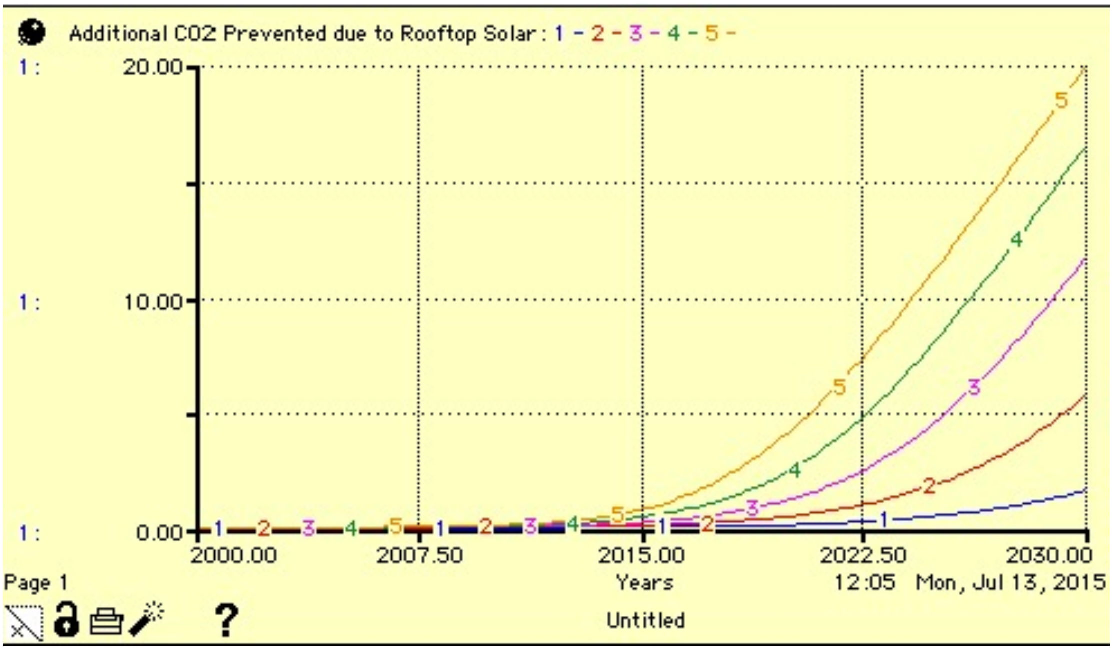


Figure 18 - effects of variation in Willingness to Adopt variable on addition in rates due to rooftop solar

This variation also results in the following variations in the CO_2 emissions prevented due to rooftop solar:



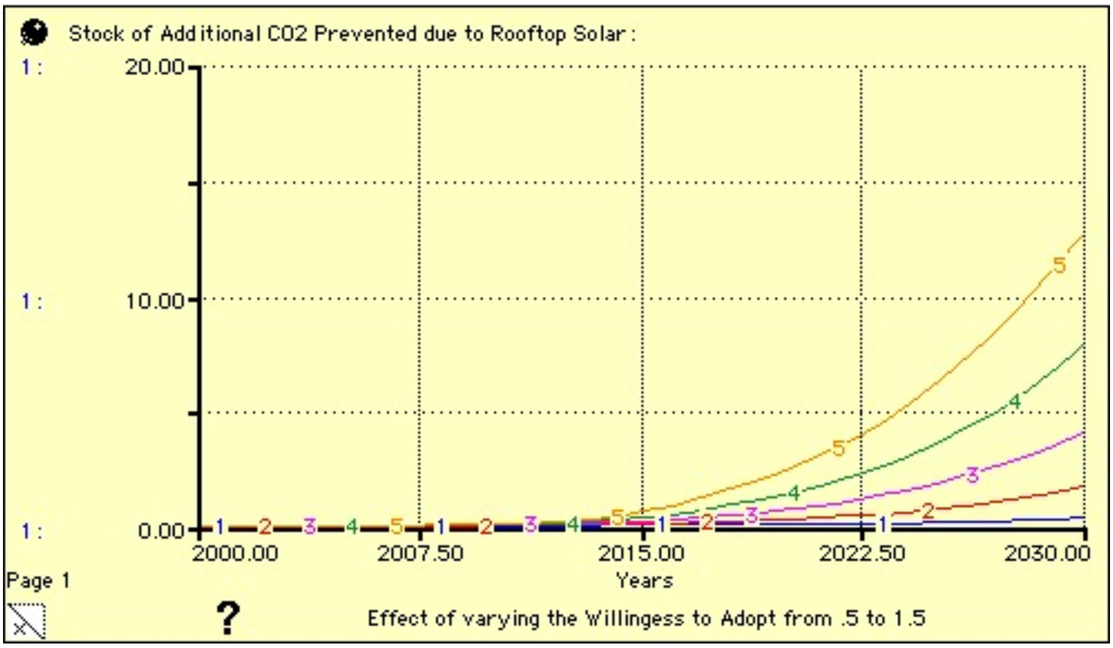


Figure 19 - effects of varying the Willingness to Adopt variable on the additional CO2 emissions prevented by rooftop solar

Here we see that variations in this variable have a significant effect on CO_2 emissions prevented, but a relatively small effect on the addition in rates due to rooftop solar.

Other variables that were used in sensitivity analyses were:

- The price of RECs
- Price of utility scale solar relative to residential scale solar
- The annual growth rate in demand in SRP's service area
- The fraction of Renewable Energy Portfolio that would be achieved by SRP without rooftop solar diffusion.
- The average MWs installed per rooftop solar adopter
- Natural Gas plant variable costs per MWh

Realistic variations in all of these variables produced relatively robust results, thus validating the model in terms of sensitivity analyses. The most sensitive parameters were those whose test results were displayed above, with the rate of growth of SRP's Base Case rates being perhaps the most sensitive.

3. Behaviour Pattern Tests – can the model produce the actual behaviour of the real-life system?

This question is usually answered by evaluating the model's ability to reproduce the reference model, which is the historic behaviour of an important variable in the model [54]. However in the case of this model, it seems that a proper reference mode test cannot be done. There are several reasons for this:

Regarding the first ‘reference mode’ of SRP’s rates, it is clear that the model will replicate this behaviour, because I have taken the ‘Base Case’ SRP rates as exogenous data, and the model does not add to the historical part of the data until after 2013 (the last available year of data), for reasons discussed during the model description.

As regards rooftop solar diffusion, the graphical function determining this was calibrated against real data, and so it too will match with the historical data, but not for the right reasons.

Finally, regarding CO_2 emissions, the other reference mode variable, the model simulates the CO_2 *saved* as a result of rooftop solar alone. Understandably, such data (CO_2 saved) could not be found. Data *could* be found on the stock of SRP-owned solar, which is a proxy for the total CO_2emissions saved by solar. However, the accuracy of this variable is almost entirely unimportant to the model. This is because, again, we are looking for the CO_2 saved as a result of rooftop solar diffusion alone. The important variables in the model are the additional CO_2 saved by rooftop solar, and the addition in rates due to rooftop solar. These are determined by the *displaced* investments in SRP’s own solar. As such, whether SRP have (or desire to have) 1000 or 2000 MWs of solar, rooftop solar diffusion of 20 MWs will still have the same displacement effect on SRP’s investments. Therefore the stock of SRP-owned solar is unimportant to the model’s results. This means that there exists no useful data against which we can validate the model’s results concerning CO_2 emissions saved.

The main justification I can have for this lack of a reference mode test is that the problem hasn’t really happened yet in the U.S., and so there is no problematic behaviour to replicate. The only other known system dynamics study that has dealt with the ‘death spiral’ problem, which focused on the case in Australia, also did not seek to replicate any historic behaviour, as it started its simulations in 2015 [2].

Nonetheless, one source of confidence we *can* have in the model in terms of behaviour pattern is that it produces relatively plausible results of what could happen in the future. For example, the extent to which rooftop solar diffusion affects utility rates in Scenario 1 seems plausible (it increases it by 8.3% by the end of 2030).

To conclude the assessment of the model’s validity, we can note that the model mainly derives its validity from structure and structure-oriented tests. The behavioural tests could not be quantitatively validated (for the reasons expressed above), but instead has been validated through personal assessment

about their plausibility. As Barlas (1996) has argued, the validity of a model is dependent on its purpose. Seeing as the purpose of this model is to analyse and generate insight towards a problem which is still more or less latent, we can accept the fact that some behavioural tests may not be carried out.
Having built some confidence in the validity of the model, we can now turn to analyse its simulation results.

7. Model Behaviour

What results does the model produce in Scenario 1?

In Scenario 1 (which is described on page 40), the model produces the following diffusion of rooftop solar, with rooftop solar adopters presented as a fraction of all of SRP's residential customers.

Figure 20 - Scenario 1 run for rooftop solar diffusion

Note that the growth of this stock is exponential. This is due to the falling PV prices, the increasing Base Case rates, as well as the effects of the model's five reinforcing feedback loops. Note that in 2016 there is a slight decrease in the exponential growth path of rooftop solar adopters. This is because the residential renewable energy tax credit expired for rooftop solar systems in this year, thus increasing their payback periods and reducing their rate of adoption.

How are SRP's rates affected by the rooftop solar diffusion in Scenario 1?

In this Scenario 1, rooftop solar diffusion has the following effect on SRP's rates (again, all prices show are in U.S. dollars):

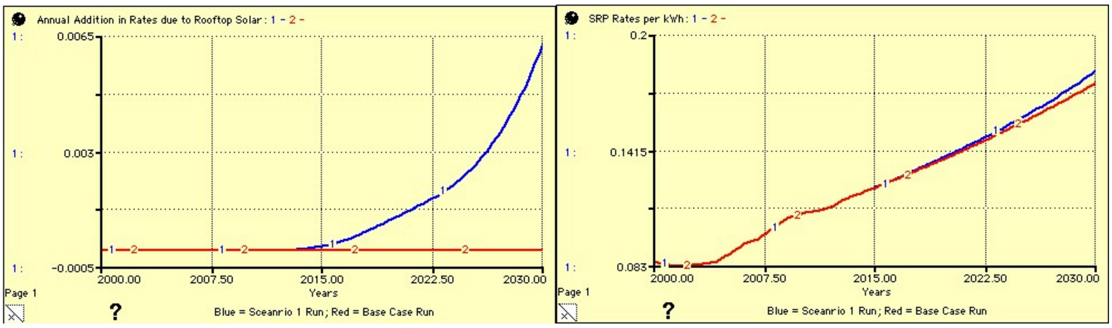


Figure 21 - Effect of rooftop solar on SRP's rates in Scenario 1

The Base Case rates have been shown alongside the actual rates so that the reader can get an idea of the magnitude of the addition in rates. Remember that the addition in rates has no effect on the actual rate until after 2013, because such additions should already be reflected in the historical data that is used up until this point. This is why the rate remains the same as the Base Case rate up until 2013. Either way, the addition in rates is practically negligible up until 2016 (as can be seen in the graph on the left in figure 21). However, after this point it can be seen that rooftop solar diffusion does result in some noticeable addition to the Base Case rates.

By the end of the simulation period, SRP’s rates are $.0147 higher than they would be if there had been no rooftop solar diffusion. This is an increase of 8.3% from the Base Case rate. The increase in rates seen here is caused directly by SRP’ profit lost as a result of rooftop solar. This happens because the lost revenues due to rooftop solar are greater than the costs avoided due to rooftop solar. This happens in Scenario 1 because SRP receive/claim no RECs. This means that their avoided costs come solely from avoided variable costs, as in this scenario they cannot avoid any generation capacity investment costs. Thus the avoided costs are less than the lost revenues, resulting in lost profits for SRP, which in turn causes them to make additions to their normal rates. These lost profits accumulate to $933,371,580 profits lost by the end of 2030. Throughout the simulation period these lost profits translate into additions to their Base Case rates. Such a result validates the cross-subsidization hypothesis, at least in the context of Scenario 1. It also serves as a proxy indication of security of supply issues, as the significant lost revenues experienced by SRP would likely result in their investors being less willing/able to invest in new infrastructure.

Does the model validate the death spiral hypothesis in Scenario 1?

The death spiral essentially says that rooftop solar diffusion will be largely reinforcing due to its effect on the utility’s rates. Thus to properly test this hypothesis, we need to determine how much the increase in rates due to rooftop solar actually affects the diffusion of rooftop solar. This can be done by comparing simulation results for the Scenario 1 diffusion with the diffusion when the death spiral loop (R1) is cut. This loop can be cut by multiplying the 'addition in rates due to rooftop solar' variable by zero. The results are displayed below:

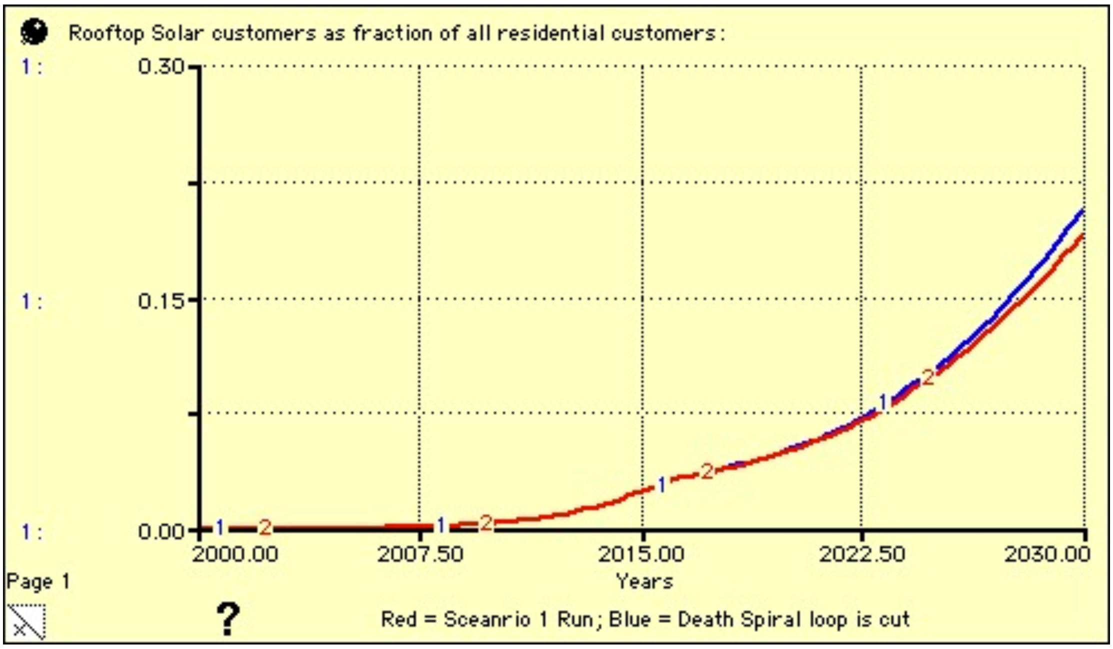


Figure 22 - effect of the death spiral loop on rooftop solar diffusion

We see that the feedback effect between rooftop solar diffusion and increased utility rates does indeed result in greater rooftop solar diffusion. However, the result may not be dramatic enough to warrant the term 'death spiral'. In Scenario 1 (the Red run), there are 242,276 rooftop solar adopters in SRP's service area by the end of 2030. This is roughly 21% of the residential customers that SRP is expected to have by 2030. If rooftop solar did not result in any addition in rates (i.e. the Blue run), then the model projects that there would still be 223,242 rooftop solar adopters in SRP's service area by the end of 2030, which is roughly 19% of the expected residential customers for that year.

In comparison to this, the rate at which rooftop solar's installed cost declines seems to be a more important factor in determining rooftop solar's diffusion (and the resulting effect on SRP's rates). This can be seen in the graph below, where the annual rate of cost reduction of rooftop solar has been varied from the MEDIUM cost reduction scenario (at an annual rate of .06 until 2013, and then declining linearly to .008 by 2030) to the HIGH cost reduction scenario (remaining at a rate of .06 from 2000 to 2030).

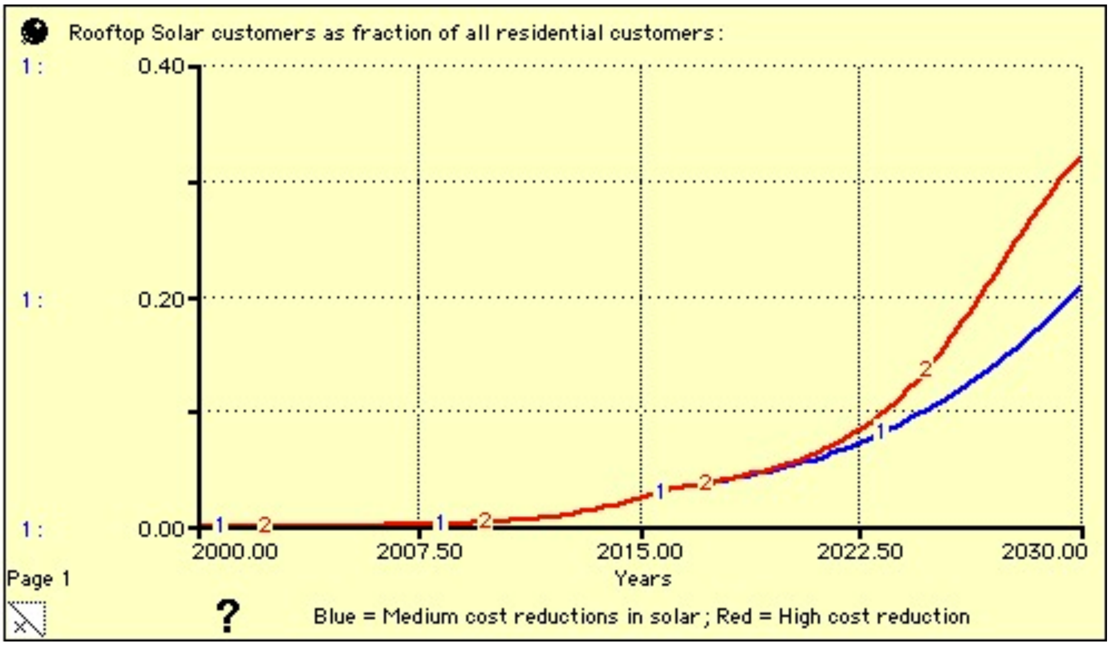


Figure 23 - effect of higher PV cost reductions on rooftop solar diffusion

Comparing figures 22 and 23, we see that the change in the cost reduction rate of rooftop solar has a greater effect on rooftop solar diffusion than the death spiral effect does.

How does rooftop solar affect CO_2 emissions in Scenario 1?

As seen in the figure 24, rooftop solar diffusion in Scenario 1 results in an additional 5.73 million metric tons of CO_2 emissions prevented by the end of the simulation period.

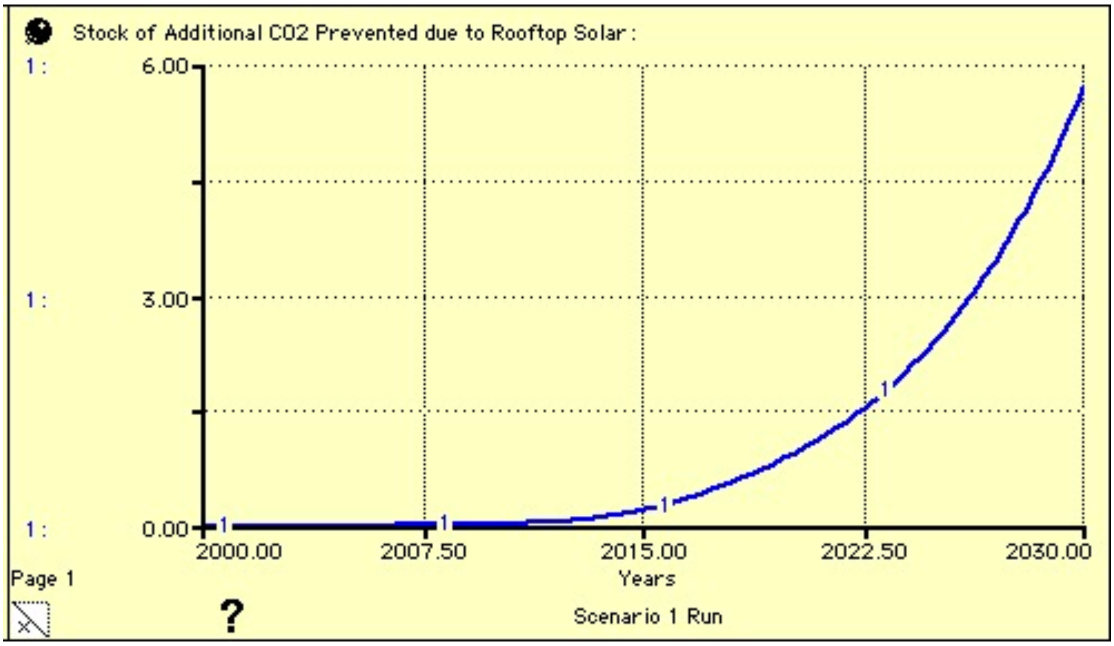


Figure 24 - CO2 emissions prevented due to rooftop solar in Scenario 1 (Units in Million Tons of CO2)

Note that these avoided CO_2 emissions are dependent on two things in the model – (i) the diffusion of rooftop solar, and (ii) the fraction of rooftop solar systems from which SRP claim RECs.

That concludes our discussion of the model behaviour in Scenario 1. In the following chapter we will use the model to evaluate different policy options by analysing the results of changing different policy parameters in the model.

8. Policy Analysis

Which are the policy variables in the system, i.e. which variables can be directly controlled by policy makers?

Most of the model's inputs are more or less outside of the control of any policy maker. For example, neither the demand for SRP's electricity nor the global price of PV systems are directly determinable through SRP's or the government's policies. However there are three parameters which are directly determinable by the system's policy makers. The ones most easily controlled by SRP are:

- The fraction of rooftop solar systems from which SRP claims/buys RECs.
- The annual increase in rooftop solar customers' bills due to the new rate plan.

The main policy variable that can be controlled by the U.S. government is:

- The tax credit for residential solar systems after 2016[xvii].

Readers should note that the U.S. government could also have influence over how RECs are used, via RPS requirements/restrictions. Furthermore, in most contexts the U.S. government could also have influence over the policy of a special rate plan for solar customers. This is because most U.S. electric utilities are regulated, meaning that new rate plans could only be proposed by the utility and then accepted or rejected by the state commission that regulates them. In the context of this study, however, SRP is a publicly owned utility and so it essentially regulates itself, via its publicly elected board of directors.

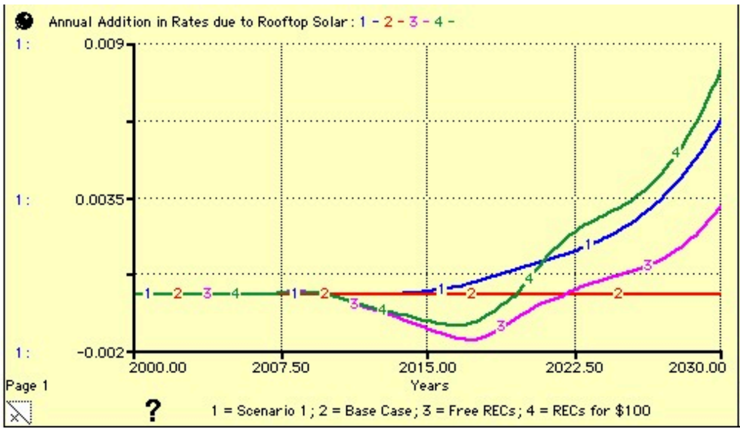
In this chapter we will analyse how varying the three policy parameters above will affect SRP's rates and its CO_2 emissions.

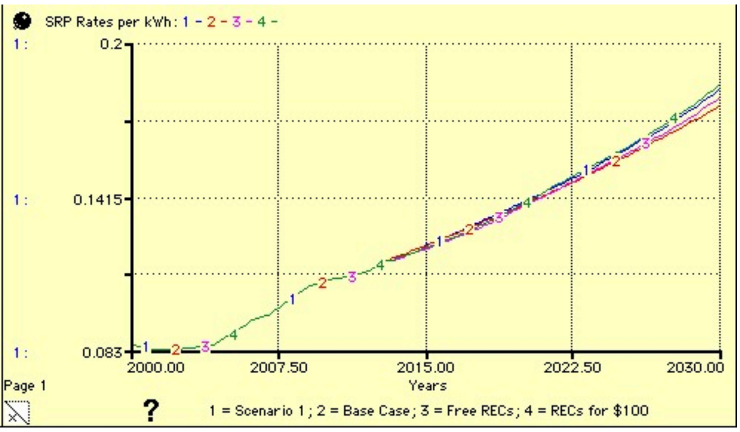
How does changing the fraction of RECs claimed by SRP affect their rates?

In Scenario 1, analysed in Chapter 6, SRP claimed none of the RECs from their customers' rooftop solar systems. We will now analyse what happens if SRP claims *all* of the RECs from their customers' rooftop solar systems (i.e. if we change the 'fraction of rooftop solar systems from which SRP claim RECs' from 0 to 1). In one run (Run 3), we see what happens if SRP claim these RECs for free.

[xvii] Other subsidies such as net metering could also be controlled by the government, but for the sake of simplification the model does not represent these subsidies. The effects of such subsidies would essentially be the same as the tax credit anyway – they would reduce the payback period of rooftop solar, and thus stimulate greater diffusion.

In reality, however, SRP is likely to have to pay their customers for these RECs. As such we also analyse what happens if they have to pay a price of $100[xviii] (Run 4) per REC (i.e. per MWh of output from their customers' rooftop solar systems). These scenarios will be compared against Scenario 1 runs, so that the effects of these policy parameters can be seen. Additionally, the Base Case (i.e. the case of no rooftop solar diffusion) scenario will also be presented, so that the magnitude of the effect of rooftop solar can be seen.





In the Base Case run, there is no rooftop solar diffusion and thus no addition in rates due to rooftop solar. As already discussed, Scenario 1 results in an increase in rates of 8.3% by the 2030. In the 'all RECs for free' (Run 3) case, there is initially a *decrease* in rates. This is because the RECs allow SRP to forego investments in their own solar capacity each year. Avoiding the cost of these investments means that rooftop solar diffusion actually results in *more* 'costs avoided due to rooftop solar' than 'revenues lost due to rooftop solar'. This results in an initial decrease in rates, because SRP's Board of Directors should recognize the fact that SRP should now be able to afford lower rates whilst maintaining cost recovery. However, as seen in the results above, this decrease in rates is only temporary. This is because the main part of these avoided costs come from the 'annual generation capacity investment costs avoided due to rooftop solar', which is based on a flow – the annual rooftop solar installations. On the other hand, the annual lost revenues are directly determined by a stock – the MWs of rooftop solar in SRP's service area. Initially, the effect of this flow outweighs the effect of the stock. However, as the MWs of rooftop solar installed accumulates over time, it eventually begins to outweigh the effects of the flow. In Run 3, this happens at year 2020.

[xviii] One study has noted that the price of RECs for solar has ranged between $45 and $250[66].

In the 'all RECs for $100' scenario (Run 4), similar behaviour is seen. However the initial decrease in rates is less because SRP's costs will be increased $100 for every REC bought. Furthermore, the eventual increase in rates is greater, for the same reason.

How does changing the fraction of RECs claimed by SRP affect the CO_2 emissions prevented?

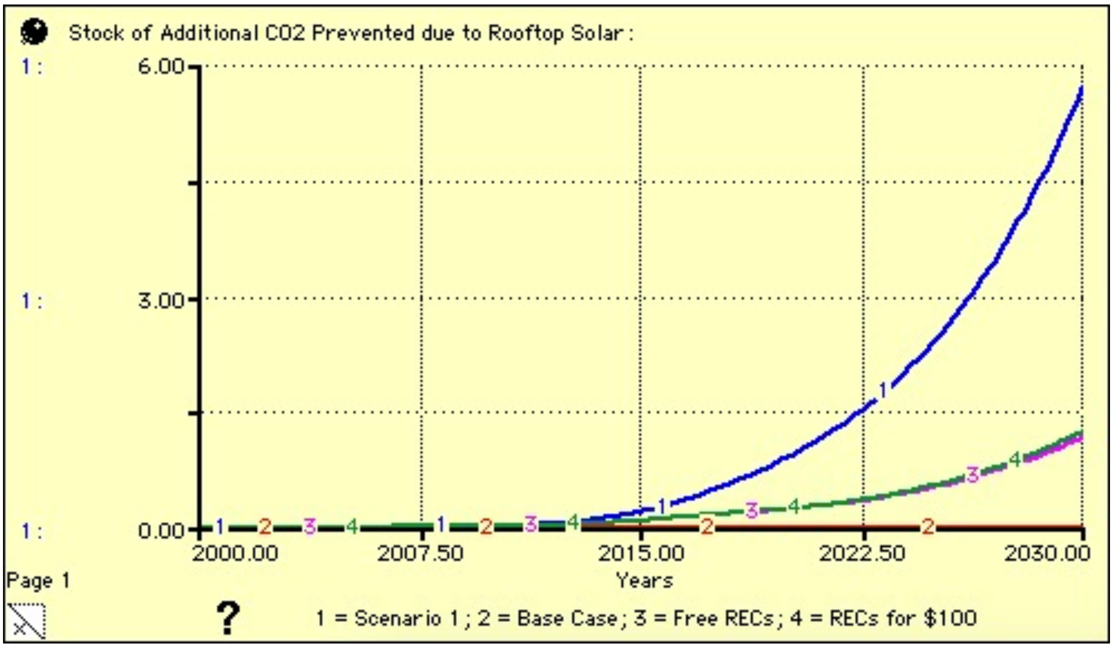


Figure 26 - Effect of REC policy on CO2 emissions prevented due to rooftop solar

In figure 26 we see that Scenario 1 results in the most CO_2 emissions being prevented. This is because SRP does not balance its investments in its own solar in this case. When SRP does receive the RECs, then they will balance their investments in their own solar, and less emissions are saved, as seen in Run 3 and Run 4 above. In other words, in this scenario every MW of rooftop solar installed will result in SRP eventually investing in 1 less MW of their own solar.

Nonetheless, the simulations reveal that some additional emissions are still saved. This is because SRP reduce their investments *after a delay in perceiving rooftop solar installations.* This delay is seen in the model when rooftop solar installations flow into the stock of 'MWs of solar from which SRP claim RECs'. The flow is not accumulated into this stock until after 1 time-step, which in this model is one year, meaning that there is a delay effect present. This delay means that SRP will not balance its investments immediately, which means that every rooftop solar installation will not result in balanced investments *until 1 year after the installation.* This means that more MWs of solar will come online quicker than it would otherwise have been (if there had been no rooftop solar diffusion), which in turn prevents CO_2emissions that would otherwise not have been prevented. In other words, rooftop solar diffusion allows SRP to achieve its RPS goals quicker than it was planning to, and thus helps to prevent more CO_2 emissions. However it should be noted that if SRP began to make projections about rooftop solar diffusion and to rely on receiving a certain number of RECs from these future systems, then they may balance their investments earlier, meaning that rooftop solar diffusion would result in no extra CO_2 emissions prevented.

As regards the effect of the price of RECs, there is very little difference between the results for the 'All RECs for free case' and the 'All RECs for $100' case (Run 3 and Run 4, respectively). This is because, as discussed in chapter 7, the increase in rates due to rooftop solar has been shown to have little effect on its diffusion (i.e. loop R1 has little effect of rooftop solar diffusion), and so will, by extension, have very little effect on the additional CO_2 emissions prevented due to rooftop solar.

How does SRP's new rate plan affect their rates?

As discussed in Chapter 2, SRP has recently introduced a special rate plan for their solar customers, which is expected to increase the monthly bills of their average distributed generation customer (such as rooftop solar owners) by $50 [15,78]. However, existing rooftop solar customers have been grandfathered for 20 years [15,78]. In the model this affects both diffusion of rooftop solar (by lowering the expected savings of rooftop solar) and SRP's profits lost as a result of rooftop solar (by decreasing SRP's profits lost for every MW of rooftop solar installed after 2015). The graph below compares the Scenario 1 run with a run of the same conditions, except that the effects of the new rate plan have been introduced. The Base Case run has also been included, so that the magnitude of the effect of rooftop solar can be easily seen.

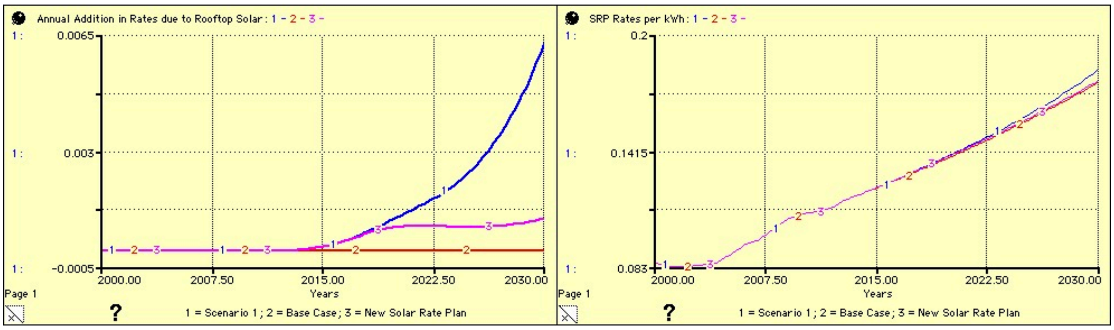


Figure 27 - effect of SRP's new rate plan on addition in rates due to rooftop solar

How does SRP's new rate plan affect rooftop solar diffusion and CO_2 emissions?

The left hand graph below compares the rooftop solar diffusion in Scenario 1 with the diffusion in the scenario in which the effects of SRP's new rate plan are included. Without the introduction of the fee, 21% of SRP's customers are projected to install rooftop solar by the end of 2030. With the introduction of the fee, the diffusion slows down from 2015 onwards such that only 5% of their customers have installed rooftop solar by the end of 2030. This is because SRP's new rate plan will decrease the expected savings from rooftop solar, as well as decrease the addition in rates due to rooftop solar. Both of these effects will (all else equal) increase the expected payback period of solar, which will slow its diffusion.

The right hand graph below shows how the introduction of the new rate plan and resulting effect on rooftop solar diffusion will affect the CO_2 emissions prevented due to rooftop solar.

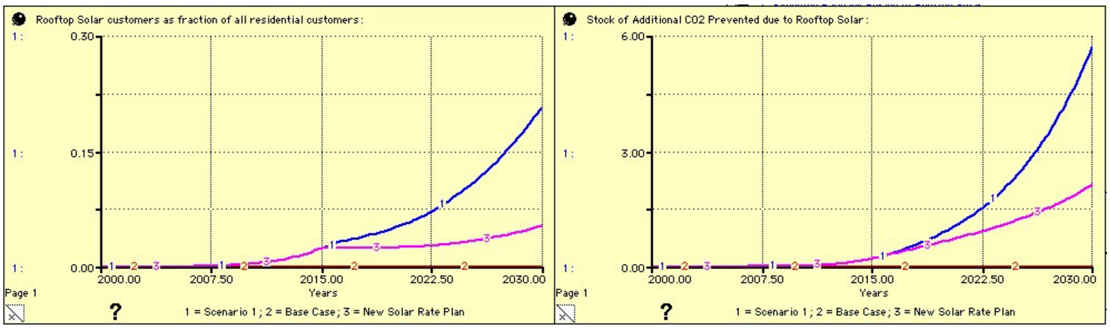


Figure 28 - effect of SRP's rate plan on rooftop solar diffusion and CO2 emissions prevented

How does changing the tax credit affect SRP's rates?

The residential renewable energy tax credit grants homeowners who install rooftop solar systems (and other micro renewable generation technologies) a tax credit worth 30% of the installed cost of their system. This tax credit is due to run out in 2016, and there is much debate about whether or not it should and will be renewed for rooftop solar systems [79]. In Scenario 1, the tax credit was not renewed. In this policy analysis section, we will see what happens when the tax credit is maintained at 30% from 2016 on.

The graph below compares the Scenario 1 run with a run of the same conditions, except that the tax credit is maintained after 2016. The Base Case run has also been included, so that the magnitude of the addition in rates can be easily seen.

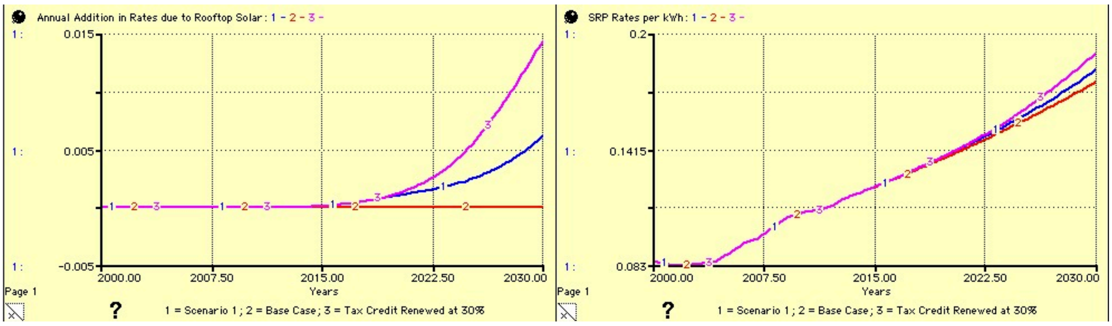
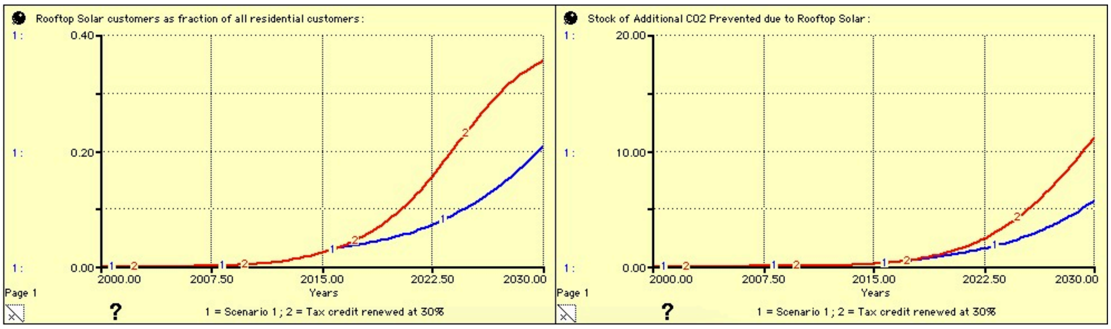


Figure 29 - the effect of renewing the tax credit on the addition in rates due to rooftop solar

The graph below then shows how renewing the tax credit will affect rooftop solar diffusion and the resulting CO_2 emissions prevented by this diffusion.



In Scenario 1, when the tax credit is not renewed, the model projects that 21% of SRP's customers will have installed rooftop solar by the end of 2030. When the tax credit *is* renewed at 30%, 36% of SRP's customers are projected to have installed rooftop solar. However the financial costs of this tax credit should also be taken into account. The model's side calculations reveal that in Scenario 1, the government foregoes $200,492,685 in tax credits for residential rooftop solar installers by the end of 2030. When this tax credit is renewed at 30% in 2016, the model projects that the government will forego $1,923,640,729 by the end of 2030. Such costs should also be taken into account when analysing the effectiveness of renewing the tax credit.

To conclude, this chapter has reviewed the effects of changing three policy parameters – (i) the fraction of rooftop solar systems from which SRP claims RECs, (ii) the introduction of a special rate plan for SRP's rooftop solar customers, and (iii) the non-renewal of the tax credit after it runs out in 2016. The effects of changing these policy parameters can be summarized in the following table:

Policy	**Effect on rooftop solar diffusion**	**Effect on SRP's rates**	**Effect on CO_2 emissions prevented**
Claim all RECs (in RECs free scenario)	Minimal	Initially allows for reductions from Base Case rate, followed by additions from 2020 on	Results in less CO_2 emissions being prevented, due to SRP balancing their investments
Claim all RECs (when RECs are $100)	Minimal	Initially allows for small reductions from Base Case rate, followed by larger additions from 2022 on	Results in less CO_2 emissions being prevented, due to SRP balancing their investments
Introduce special solar rate plan	Greatly reduces diffusion	Allows for almost no rate additions to be needed	Results in much less CO2 prevented
Renew tax credit after 2016	Greatly increases diffusion	Exacerbates rate additions	Increases CO2 emissions prevented

Having reviewed the effects of changes in the model's main policy parameters, we can now turn to look at the limitations of this study, and the recommendations for further work on this topic. Discussion of the implications of this policy analysis will be saved for the concluding chapter.

9. Limitations and Recommendations for Further Work

What are the main limitations of this study?

With limited time and availability of data, there were several limitations to this study. The most notable limitations were as follows:

- There was no focus on the effect of solar storage technology, which could affect SRP's avoided costs and thus their rate additions.
- Didn't include SRP's costs and other factors determining the way their rates are formed.
- Didn't include commercial scale rooftop solar.
- Didn't include the benefits/costs of rooftop solar to the grid.
- Didn't include the effect that higher rates may have on SRP's customers' energy efficiency, which results in another vicious loop of reduced demand, reduced revenues, higher rates, and thus again reduced demand.
- Doesn't go into detail about customer rates – the difference between onpeak and offpeak rates in time-of-use rate plans. Also the effects of decoupling, which in one study was shown to help prevent lost revenues[6].
- Didn't include the savings experienced by rooftop solar owners

I would say that lack of inclusion of the effects of rooftop solar on the utility's grid costs is the biggest limitation to this study, as this variable could have a significant effect on SRP's profits, which in turn would have significant effects on the validity of the cross subsidization and death spiral hypotheses.

What are my recommendations for further work on this topic?

The growth of rooftop solar and the resulting concerns of utilities are quite recent affairs. Although there have been several studies already conducted on these topics [2,9,50,80], there is much work that remains to be done. My recommendations for this future work are as follows:

- Include the effects of rooftop solar in relation to microgrid formation
- Include the effect of rooftop solar on grid costs – not yet known whether this will increase or decrease grid costs overall. Could depend on where in the gird the rooftop solar systems are installed
- Include greater accuracy in the word of mouth diffusion part of the model.
- Include effects of how a more centrally planned diffusion process (as could be done by utilities, for example) could bring about greater net

benefits. For example, west facing panels may be better at meeting peak demand than south facing panels, although south facing panels produce more kWhs. As such, some incentives for west facing panels may be necessary. Additionally, certain locations in the grid will benefit from the reduced load resulting from rooftop solar more than others.

- Include effect of distributed generation on security of supply [81].
- Include greater accuracy of avoided variable costs – does rooftop solar also allow for avoided operation and maintenance costs, or only for avoided fuel costs?

What is my main recommendation for further work on this subject?

The use and price of RECs had a significant effect on model behaviour in this study, yet I was unable to find clear literature on how the RECs resulting from rooftop solar systems are being used by SRP. As such, I feel that this is the most important issue for further research on this topic.

10. Conclusions

What is the main insight of the thesis?

The main insight arising form this thesis is that, based on the assumptions made in the model, if SRP does *not* claim or buy any RECs from their customers' rooftop solar systems, then rooftop solar is shown to reduce their revenues more than it reduces their costs, in both the long term and the short term. This means that SRP would likely raise rates in compensation (or will at least have higher-than-otherwise rates), thus validating the cross subsidization hypothesis.

The model also shows that this increase in rates would encourage greater rooftop solar diffusion, thus validating the death spiral hypothesis. However, this feedback effect between rooftop solar diffusion and utility rates is quite minimal in the model, and does not have as much of an effect as does falling global PV prices. This conclusion is consistent with another system dynamics study looking at the death spiral in an Australian market [2]. Thus it seems that falling PV prices are likely to be the main driver behind rooftop solar diffusion. Finally, in this 'no RECs received' scenario, rooftop solar diffusion will have a considerable effect on CO_2 emissions, preventing 5.73 million emissions by the end of 2030.

However, in the policy analysis section it is revealed that if SRP *does* claim/buy all the RECs from its customers' rooftop solar systems, then they may (depending on the price paid for these RECs) be able to *temporarily* avoid more costs than lose revenues. This is because the RECs allow the utility to avoid investments in its own renewable generation capacity, which it would otherwise have had to make in order to meet its RPS. If the utility really can temporarily avoid more costs than lose revenues as a result of rooftop solar, then both the 'death spiral' and 'cross subsidization' hypotheses could be *partially* rejected, because rooftop solar diffusion should result in *temporarily* lower-than-otherwise rates.

However, there is a trade-off occurring in this scenario – if installation of rooftop solar systems allows utilities to invest less in their own renewable generation capacity, then rooftop solar diffusion will no longer have the effect of increasing the stock of solar present in the utility's service area. In other words, if an SRP customer were to install a 4kW rooftop solar system, and if that allowed SRP to avoid 4kWs of investment in their own solar, then the action of the SRP customer would have very little effect on the prevention of CO_2 emissions. However, it will also mean that the customer's rooftop solar system will *not* increase SRP's rates, or will at least increase them by less than in if the RECs were not claimed.

What conclusions could utility managers draw from these simulation results?

From a utility's perspective, the main finding would be that the problem of lost revenues as a result of rooftop solar diffusion could be most effectively tackled by claiming the RECs from their customers' rooftop solar systems. If these RECs are sufficiently cheap, then they could help the utility to at least temporarily reduce/overcome the impact of lost revenues resulting from rooftop solar, by way of allowing the utility to avoid investments in their own solar capacity. Additionally, the simulations have shown that introduction of SRP's new rate plan (which will increase the monthly bills of a typical rooftop solar customer by $50) would solve the problem of rate additions almost entirely, but may still result in some lost profits for the utility.

What conclusions could government policy makers draw from these simulation results?

From a government/social perspective, there are three main questions addressed in this study. The first question concerns how the Renewable Energy Certificates arising from residential rooftop solar systems should be regulated. The government faces a trade-off situation here – if they allow/encourage/force the utility to claim the RECs arising from rooftop solar systems, then this *may* (depending on the price of the RECs) result in less additions in rates due to rooftop solar, which avoids the social problem of cross-subsidization. However, this policy will also result in the utility investing less in its own solar, which means less CO_2 emissions prevented, and thus less help in achieving the U.S.'s carbon emissions targets.

The second question for the government concerns the allowance of special rate plans for utilities' rooftop solar customers. The government's acceptance or rejection of such rate plan proposals should be informed by the use and price of RECs. If no RECs are being received by the utility, then rate increases will occur, which is socially problematic from the government's point of view. In such a scenario, the special rate plans seem justified. On the other hand, if the RECs of rooftop solar systems *are* being claimed by the utility and at a sufficiently low price, then an increase in the monthly bills of rooftop solar customers would be unnecessary. This is because the avoided costs are almost as large as the revenues lost in this scenario. For example, in the 'all RECs for free' scenario, introducing SRP's new special rate plan (which increases the monthly bills of an average solar customers by $50) would result in SRP temporarily making an overall profit as a result of rooftop solar diffusion, because they avoid many costs and also achieve higher revenue from the new rate plan. Nonetheless, even in this scenario, the utility's avoided costs are eventually outweighed by the lost revenues caused by the growing stock of rooftop solar systems.

Perhaps the main problem with these special rate plans is that they may have a negative effect on rooftop solar diffusion. For example, simulations show that if the tax credit is not renewed, and if SRP's new rate plan for solar customers was introduced, then the model projects that rooftop solar installations would drop to zero for all of 2016. Although installations would pick up again from 2017 onwards, as global PV costs continue to decline, the overall stock of rooftop solar would be reduced significantly (from 1090 MWs in 2030 in Scenario 1, to 282 MWs in this scenario).

In addition to discouraging rooftop solar diffusion, SRP's proposed rate plan could have another downside – it seeks to guarantee cost recovery by charging higher fixed costs and proportionately lower variable costs (particularly at off-peak times) [15]. These lower variable costs (i.e. the price per kWh used) could discourage energy efficiency, which would have a negative environmental effect. It could also have a disproportionately negative effect on low-usage rooftop solar households (many of whom may be lower income households), as the increased fixed costs would increase bills more noticeably.

The third and last question for the government concerns the renewal of the tax credit after 2016. State policy makers may wonder if this tax credit could be more effectively used elsewhere. If utilities are claiming the RECs of rooftop solar systems, and if this causes utilities to balance investments in their own solar, then it begs the question – is rooftop solar the most efficient way for a utility to meet its RPS, and should the government be subsidising this way of achieving the RPSs? One argument *against* the renewal of the tax credit would be that this tax credit does not promote the most efficient and socially equitable way of achieving utilities' RPSs. The tax credit policy is not socially equitable because most of the credits go to middle and higher income households [48], and because rooftop solar results in higher rates in almost all of the scenarios studied in the model. Additionally, rooftop solar may not be the most efficient way of achieving an RPS – one study has shown that utility scale solar has been between 30 and 40% cheaper than residential scale solar, per installed MW [9]. Thus, one may argue that state subsidies would be more efficiently used if they were solely directed at larger scale solar projects. This is because, firstly, it would avoid the cross-subsidization problem. Secondly, it may still encourage solar diffusion by allowing the government to set higher RPS standards (and thus prevent more CO_2 emissions), seeing as the utility is now receiving more help to achieve this goal (after the tax credit 'budget' has been redirected from residential to utility scale solar).

However, the above arguments against the renewal of the tax credit for rooftop solar ignore two things. Firstly, they do not consider the potential benefits to the grid that distributed generation sources may bring. Such benefits have been ignored in this study, due to a lack of clear frameworks for calculating them [82]. Secondly, these arguments ignore the fact that the diffusion of distributed generation resources is based on customer choice, which may be the most effective way of bringing about greater diffusion of renewables. Indeed, looking at Germany, one of the most successful countries in terms of diffusion of renewables, it is interesting to note that in 2013 over half of the capacity in their two largest renewable sources of energy (wind and solar) was owned by individuals, farmers and industry actors, whilst just 5% was owned by big utilities and 7% by regional/municipal utilities [47]. Thus it is clear that distributed customer-owned generation, driven by the power of customer choice and government subsidies, has been a major factor in Germany's highly successful renewable energy transition. Following from this, environmentalists may argue that the government should focus more on stimulating the demand for renewables from a grass-roots basis, i.e. via the choices of individual households and small-scale businesses. Indeed, it could be argued that large-scale industry actors such as utilities cannot be relied on to make the investments necessary to combat climate change.

Is there a better way to diffuse solar power?

All of the policy options discussed above have some trade-offs between rate increases and CO_2 emissions prevented. Thus it is natural to ask, is there any policy that could avoid such trade-offs? There may be. From my perspective, the best way to diffuse solar technology would be to encourage/subsidize community scale solar projects. Such projects already exist, and are usually offered by utilities. The utility's customers may participate in the solar project by 'contributing either an up-front or ongoing payment to support a solar project. In exchange, customers receive a payment or credit on their electric bills that is proportional to 1) their contribution and 2) how much electricity the solar project produces' (Page 8, from reference [83]).

There are five reasons for which I feel that this is the best way to diffuse solar technology. Firstly, it allows all electric customers (regardless of whether they live in a home or an apartment) an equal opportunity to avail of solar energy. This would alleviate the cross-subsidization problem. Secondly, the utility should be able to benefit from any profits to be made from such projects, which should allow them to charge lower rates. Thirdly, these medium/large solar projects will benefit from economies of scale and reduced administration costs, keeping the overall costs lower, and making solar energy more competitive. Fourthly, if the solar plants can be located close to the point of consumption, then this will reduce load losses on the grid. It will also not require grid updates to accommodate a two-way flow of electricity, seeing as the electricity would only flow from the plant to the point of consumption. Lastly, this way of encouraging diffusion of solar still relies on the powerful force of consumer choice, which in the context of Germany appears to have been a major factor in the success of their transition to renewable energies.

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Appendix A – Model Equations

The model runs in years, with a DT of .25.

Accumulated_CO2_Preveneted_by_All_Solar(t) =
Accumulated_CO2_Preveneted_by_All_Solar(t - dt) +
(CO2_Saved_per_Year_by_Solar) * dt
INIT Accumulated_CO2_Preveneted_by_All_Solar = 0

INFLOWS:
CO2_Saved_per_Year_by_Solar =
Annual_MWhs_produced_by_All_Solar_after_Rooftop_Solar*Million_Tons_of_CO2_emissions_per_MWh_of_Natural_Gas_electricity

Accumulated_Net_Change_in_SRP_Profit_from_Rooftop_Solar(t) =
Accumulated_Net_Change_in_SRP_Profit_from_Rooftop_Solar(t - dt) +
(Annual_Change_in_Profit) * dt
INIT Accumulated_Net_Change_in_SRP_Profit_from_Rooftop_Solar = 0

INFLOWS:
Annual_Change_in_Profit = Annual_SRP_Profit_Lost_due_to_Rooftop_Solar*-1

Perceived_Annual_Profits_Lost_due_to_RS(t) =
Perceived_Annual_Profits_Lost_due_to_RS(t - dt) +
(Change_in_perceived_profits_lost) * dt
INIT Perceived_Annual_Profits_Lost_due_to_RS = 0

INFLOWS:
Change_in_perceived_profits_lost =
(Annual_SRP_Profit_Lost_due_to_Rooftop_Solar-Perceived_Annual_Profits_Lost_due_to_RS)/Time_to_Perceive_Money_Lost

Accumulated_CO2_Prevented_by_Rooftop_Solar(t) =
Accumulated_CO2_Prevented_by_Rooftop_Solar(t - dt) +
(CO2_Saved_per_year_by_Rooftop_Solar) * dt
INIT Accumulated_CO2_Prevented_by_Rooftop_Solar = 0

INFLOWS:
CO2_Saved_per_year_by_Rooftop_Solar =
Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems*Million_Tons_of_CO2_emissions_per_MWh_of_Natural_Gas_electricity

```
Accumulated_MWs_of_Rooftop_Solar_Installed(t) = Accumulated_MWs_of_Rooftop_Solar_Installed(t - dt) + (Annual_MWs_of_Rooftop_Solar_installed) * dt
INIT Accumulated_MWs_of_Rooftop_Solar_Installed = 0
INFLOWS:
Annual_MWs_of_Rooftop_Solar_installed = SRP_Customers_Installing_Rooftop_Solar*Average_MWs_installed_per_Rooftop_Solar_adopter

Accumulated_MWs_of_RS_installed_after_New_plan_is_introduced(t) = Accumulated_MWs_of_RS_installed_after_New_plan_is_introduced(t - dt) + (Annual_installations_of_RS_after_New_rate_plan) * dt
INIT Accumulated_MWs_of_RS_installed_after_New_plan_is_introduced = 0

INFLOWS:
Annual_installations_of_RS_after_New_rate_plan = IF TIME > Year_in_which_SRP_Special_Price_Plan_for_RS_Customers_is_enacted THEN Annual_MWs_of_Rooftop_Solar_installed ELSE 0

Additional_CO2_Prevented_due_to_Rooftop_Solar(t) = Additional_CO2_Prevented_due_to_Rooftop_Solar(t - dt) + (Additional_CO2_saved_per_year_by_Rooftop_Solar) * dt
INIT Additional_CO2_Prevented_due_to_Rooftop_Solar = 0

INFLOWS:
Additional_CO2_saved_per_year_by_Rooftop_Solar = Additional_Annual_MWhs_from_Solar_due_to_Rooftop_Solar*Million_Tons_of_CO2_emissions_per_MWh_of_Natural_Gas_electricity

Arizona_Electric_Customers(t) = Arizona_Electric_Customers(t - dt) + (Change_in_Arizona_Population) * dt
INIT Arizona_Electric_Customers = 2193407

INFLOWS:
Change_in_Arizona_Population = Arizona_Electric_Customers*Growth_rate_of_Arizona_Electric_customers

MWs_of_Rooftop_Solar_from_which_SRP_claim_RECs(t) = MWs_of_Rooftop_Solar_from_which_SRP_claim_RECs(t - dt) + (Annual_Rooftop_Solar_installations_for_which_SRP_claim_RECs) * dt
INIT MWs_of_Rooftop_Solar_from_which_SRP_claim_RECs = 0

INFLOWS:
```

Annual_Rooftop_Solar_installations_for_which_SRP_claim_RECs = DELAY(Annual_MWs_of_Rooftop_Solar_installed*Fraction_of_Rooftop_Solar_Systems_from_which_SRP_receives_RECS,Years_between_RS_Installation_and_Receiving_Contract_for_RECs,0)

Potential_Rooftop_Solar_Adopters(t) = Potential_Rooftop_Solar_Adopters(t - dt) + (Annual_Change_In_Potential_Households - SRP_Customers_Installing_Rooftop_Solar) * dt
INIT Potential_Rooftop_Solar_Adopters = 311150

INFLOWS:
Annual_Change_In_Potential_Households = Potential_Rooftop_Solar_Adopters*Growth_rate_of_Arizona_Electric_customers

OUTFLOWS:
SRP_Customers_Installing_Rooftop_Solar = RS_On_OFF_Switch*((Potential_Rooftop_Solar_Adopters*Fraction_installing_Rooftop_Solar_per_year + WOM_Effect)/Time_to_Install_Rooftop_Solar)

Projected_Annual_MWh_demand(t) = Projected_Annual_MWh_demand(t - dt) + (Annual_increase_in_Demand) * dt
INIT Projected_Annual_MWh_demand = Historical_Annual_MWh_demand

INFLOWS:
Annual_increase_in_Demand = Projected_Annual_MWh_demand*Growth_in_SRP_MWh_demand_per_year

Projected_Installed_cost_per_MW_of_Residential_Solar(t) = Projected_Installed_cost_per_MW_of_Residential_Solar(t - dt) + (Correction_until_2012_2 - Annual_change_in_Installed_cost) * dt
INIT Projected_Installed_cost_per_MW_of_Residential_Solar = 5352517.98561151

INFLOWS:
Correction_until_2012_2 = IF TIME > 2012 THEN 0 ELSE Annual_change_in_Installed_cost

OUTFLOWS:
Annual_change_in_Installed_cost = IF SCENARIO_HIGH_MEDIUM_or_LOW_Cost_Reductions_for_Residential_Solar = 1 THEN Projected_Installed_cost_per_MW_of_Residential_Solar*Fractional_reduction_in_RS_cost_per_year_HIGH ELSE IF

SCENARIO_HIGH_MEDIUM_or_LOW_Cost_Reductions_for_Residential_Solar = 0 THEN Projected_Installed_cost_per_MW_of_Residential_Solar*Fractional_reduction_in_RS_cost_per_year_MEDIUM ELSE Projected_Installed_cost_per_MW_of_Residential_Solar*Fractional_reduction_in_RS_cost_per_year_LOW

Projected_Normal_SRP_Rates_per_kWh(t) = Projected_Normal_SRP_Rates_per_kWh(t - dt) + (Flow_1 - Correction_until_2013) * dt
INIT Projected_Normal_SRP_Rates_per_kWh = 0.1171

INFLOWS:
Flow_1 = IF SCENARIO_HIGH_MED_LOW_SRP_RATES_GROWTH_RATE = 1 THEN Projected_Normal_SRP_Rates_per_kWh*Annual_growth_in_SRP_Rate_without_Roofotp_Solar_HIGH ELSE IF SCENARIO_HIGH_MED_LOW_SRP_RATES_GROWTH_RATE=0 THEN Projected_Normal_SRP_Rates_per_kWh*Annual_growth_in_SRP_Rate_without_Roofotp_Solar_MEDIUM ELSE Projected_Normal_SRP_Rates_per_kWh*Annual_growth_in_SRP_Rate_without_Roofotp_Solar_LOW
OUTFLOWS:

Correction_until_2013 = IF TIME < 2013 THEN Flow_1 ELSE 0

Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity(t) = Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity(t - dt) + (Annual_change_in_Natural_Gas_Cost_per_MWh - Correction_until_2012) * dt
INIT Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity = 30.45

INFLOWS:
Annual_change_in_Natural_Gas_Cost_per_MWh = IF SCENARIO_Natural_Gas_Variable_Costs_Growth_Rates = 1 THEN Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity*Annual_growth_rate_in_Natural_Gas_Variable_cost_1% ELSE IF SCENARIO_Natural_Gas_Variable_Costs_Growth_Rates = 0 THEN Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity*Annual_growth_rate_in_Natural_Gas_Variable_Costs_TREND ELSE Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity*Annual_growth_rate_from_2012_Natural_Gas_Variable_Cost_MINUS_1%

OUTFLOWS:

Correction_until_2012 = IF TIME > 2012 THEN 0 ELSE Annual_change_in_Natural_Gas_Cost_per_MWh
Rooftop_Solar_Adopters(t) = Rooftop_Solar_Adopters(t - dt) + (SRP_Customers_Installing_Rooftop_Solar) * dt
INIT Rooftop_Solar_Adopters = 0

INFLOWS:
SRP_Customers_Installing_Rooftop_Solar = RS_On_OFF_Switch*((Potential_Rooftop_Solar_Adopters*Fraction_installing_Rooftop_Solar_per_year + WOM_Effect)/Time_to_Install_Rooftop_Solar)
SRP_Solar_after_Rooftop_Solar(t) = SRP_Solar_after_Rooftop_Solar(t - dt) + (Annual_Investments_in_SRP_Solar_after_Rooftop_Solar) * dt
INIT SRP_Solar_after_Rooftop_Solar = 0

INFLOWS:
Annual_Investments_in_SRP_Solar_after_Rooftop_Solar = Perceived_Investments_needed_after_Rooftop_Solar/Time_for_SRP_Solar_Installations
SRP_Solar_in_Base_Case(t) = SRP_Solar_in_Base_Case(t - dt) + (Annual_Investments_in_SRP_Solar_in_Base_Case) * dt
INIT SRP_Solar_in_Base_Case = 0

INFLOWS:
Annual_Investments_in_SRP_Solar_in_Base_Case = Perceived_Investments_needed_in_Base_Case/Time_for_SRP_Solar_Installations
Subsidies_Spent_on_Rooftop_Solar(t) = Subsidies_Spent_on_Rooftop_Solar(t - dt) + (Subsidies_spent_per_year_on_RS) * dt
INIT Subsidies_Spent_on_Rooftop_Solar = 0

INFLOWS:
Subsidies_spent_per_year_on_RS = Annual_MWs_of_Rooftop_Solar_installed*Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*Tax_Credit_for_Residential_Solar

Actual_Desired_Percentage_of_Demand_to_be_met_by_Solar = SRPs_Solar_Renewable_Portfolio_Standards_for_each_year*Fraction_of_RPS_Target_that_would_be_achieved_by_SRP_without_RS

Additional_Annual_MWhs_from_Solar_due_to_Rooftop_Solar = Difference_between_MWs_of_Solar_With_RS_and_Without_RS*Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona

Adoption_from_WOM_Fraction = 0.02

Annual_Addition_in_Rates_due_to_Rooftop_Solar = SMTH1(Expected_Profit_Lost_in_Next_Year_due_to_RS/(Expected_kWh_demand_in_next_year*Fraction_of_Demand_over_which_lost_profits_from_RS_are_spread),3.5,0)

Annual_growth_in_SRP_Rate_without_Roofotp_Solar_HIGH = 0.04
Annual_growth_in_SRP_Rate_without_Roofotp_Solar_LOW = 0
Annual_growth_in_SRP_Rate_without_Roofotp_Solar_MEDIUM = 0.024

Annual_growth_rate_from_2012_Natural_Gas_Variable_Cost_MINUS_1% = -0.01
Annual_growth_rate_in_Natural_Gas_Variable_Costs_TREND = TREND(Historic_Variable_costs_per_MWh_of_Natural_Gas_Plant_Electricity,3,0)
Annual_growth_rate_in_Natural_Gas_Variable_cost_1% = 0.01

Annual_Increase_in_Revenue_due_to_higher_rates_due_to_RS = SMTH1(Annual_Addition_in_Rates_due_to_Rooftop_Solar*(Overall_Annual_kWh_Demand_from_SRP_customers*Fraction_of_Demand_over_which_lost_profits_from_RS_are_spread-Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems),2,0)

Annual_Increase_in_RS_Users_Bills_per_MW_due_to_new_rate_plan = 150000

Annual_MWhs_of_Demand_from_Residential_Customers = Overall_Annual_MWh_Demand_from_SRP_CUstomers*Percentage_of_Demand_that_comes_from_Residential_Customers

Annual_MWhs_produced_by_All_Solar_after_Rooftop_Solar = Total_MWs_of_Solar_serving_SRP_customers_after_Rooftop_Solar*Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona

Annual_MWh_Demand_for_SRP_Electricity = (Overall_Annual_MWh_Demand_from_SRP_CUstomers-Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems)*kWhs_per_MWh

Annual_Revenue_lost_due_to_Rooftop_Solar_Output = Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems*kWhs_per_MWh*SRP_Rates_per_kWh_after_Rooftop_Solar
Annual_SRP_Capacity_Investment_Costs_Avoided_due_to_RS = Avoided_Investments_in_SRP_Solar_due_to_Rooftop_Solar*Historic_and_Projected_Installed_Cost_Per_MW_Utility_Scale_Solar

Annual_SRP_Profit_Lost_due_to_Rooftop_Solar = (Annual_Revenue_lost_due_to_Rooftop_Solar_Output + SRP_Money_Spent_per_Year_on_RECs) - Annual_Increase_in_Revenue_due_to_higher_rates_due_to_RS - Annual_Increase_in_RS_Users_Bills_per_MW_due_to_new_rate_plan*Accumulated_MWs_of_RS_installed_after_New_plan_is_introduced - Total_Annual_Costs_Avoided_due_to_Rooftop_Solar

Annual_SRP_Variable_Costs_Avoided_due_to_Rooftop_Solar = Additional_Annual_MWhs_from_Solar_due_to_Rooftop_Solar*Variable_Costs_per_MWh_Natural_Gas_Electricity

Averaged_Expected_Rate_over__Rooftop_Solar_Investment = (Expected_rate_20_years_in_the_future+SRP_Rates_per_kWh_after_Rooftop_Solar)/2

Average_MWs_installed_per_Rooftop_Solar_adopter = 0.0045

Avoided_Investments_in_SRP_Solar_due_to_Rooftop_Solar =

Annual_Investments_in_SRP_Solar_in_Base_Case-
Annual_Investments_in_SRP_Solar_after_Rooftop_Solar
Contact_Rate = 1

CONVERGING_Scenario_cost_Commercial_Solar_relative_to_Residential = GRAPH(TIME)
(2000, 0.802), (2001, 0.817), (2002, 0.831), (2003, 0.856), (2004, 0.871), (2005, 0.881), (2006, 0.86), (2007, 0.849), (2008, 0.903), (2009, 0.917), (2010, 0.867), (2011, 0.835), (2012, 0.813), (2013, 0.827), (2014, 0.838), (2015, 0.853), (2016, 0.867), (2017, 0.881), (2018, 0.888), (2019, 0.903), (2020, 0.914), (2021, 0.921), (2022, 0.928), (2023, 0.935), (2024, 0.942), (2025, 0.95), (2026, 0.957), (2027, 0.96), (2028, 0.971), (2029, 0.978), (2030, 0.982)
CONVERGING_Scenario_cost_Utility_Solar_relative_to_Residential = GRAPH(TIME)
(2000, 0.698), (2001, 0.683), (2002, 0.676), (2003, 0.676), (2004, 0.673), (2005, 0.669), (2006, 0.665), (2007, 0.665), (2008, 0.662), (2009, 0.655), (2010, 0.647), (2011, 0.63), (2012, 0.633), (2013, 0.644), (2014, 0.662), (2015, 0.673), (2016, 0.687), (2017, 0.698), (2018, 0.716), (2019, 0.73), (2020, 0.741), (2021, 0.759), (2022, 0.77), (2023, 0.784), (2024, 0.795), (2025, 0.806), (2026, 0.82), (2027, 0.835), (2028, 0.849), (2029, 0.86), (2030, 0.874)

Cost_Reduction_in_Commercial_Sized_solar_systems = 0.106

DATA_Average_Commercial_Rates_in_Arizona = GRAPH(TIME)
(2000, 7.37), (2001, 7.36), (2002, 7.28), (2003, 7.09), (2004, 7.28), (2005, 7.40), (2006, 8.02), (2007, 8.27), (2008, 8.93), (2009, 9.35), (2010, 9.47), (2011, 9.50), (2012, 9.53), (2013, 9.85)

DATA_Average_Residential_Rates_in_Arizona = GRAPH(TIME)
(2000, 0.0844), (2001, 0.083), (2002, 0.0827), (2003, 0.0835), (2004, 0.0846), (2005, 0.0886), (2006, 0.094), (2007, 0.0966), (2008, 0.102), (2009, 0.107), (2010, 0.11), (2011, 0.111), (2012, 0.113), (2013, 0.117)

DATA_Commercial_Customers_Arizona = GRAPH(TIME)
(2000, 211766), (2001, 218163), (2002, 225026), (2003, 250539), (2004, 258882), (2005, 267588), (2006, 280070), (2007, 291457), (2008, 298347), (2009, 299528), (2010, 300507), (2011, 305340), (2012, 305250), (2013, 308857)

DATA_MWhs_sold_to_Commercial_Customers_in_Arizona = 1

DATA_MWhs_sold_to_Residential_Customers_in_Arizona = GRAPH(TIME)
(2000, 2.5e+07), (2001, 2.6e+07), (2002, 2.6e+07), (2003, 2.8e+07), (2004, 2.9e+07), (2005, 3.1e+07), (2006, 3.2e+07), (2007, 3.4e+07), (2008, 3.3e+07), (2009, 3.3e+07), (2010, 3.2e+07), (2011, 3.3e+07), (2012, 3.3e+07), (2013, 3.3e+07)

DATA_Residential_Customers_Arizona = GRAPH(TIME)
(2000, 2e+06), (2001, 2e+06), (2002, 2.1e+06), (2003, 2.2e+06), (2004, 2.3e+06), (2005, 2.5e+06), (2006, 2.4e+06), (2007, 2.5e+06), (2008, 2.5e+06), (2009, 2.5e+06), (2010, 2.6e+06), (2011, 2.6e+06), (2012, 2.6e+06), (2013, 2.6e+06)

DATA_Revenue_Commercial_Sector = GRAPH(TIME)
(2000, 1.6e+06), (2001, 1.6e+06), (2002, 1.6e+06), (2003, 1.8e+06), (2004, 1.9e+06), (2005, 2e+06), (2006, 2.3e+06), (2007, 2.5e+06), (2008, 2.7e+06), (2009, 2.7e+06), (2010, 2.7e+06), (2011, 2.8e+06), (2012, 2.8e+06), (2013, 3e+06)

DATA_Revenue_from_Residential_Sector = GRAPH(TIME)
(2000, 2.1e+06), (2001, 2.2e+06), (2002, 2.2e+06), (2003, 2.3e+06), (2004, 2.4e+06), (2005, 2.7e+06), (2006, 3e+06), (2007, 3.3e+06), (2008, 3.4e+06), (2009, 3.5e+06), (2010, 3.6e+06), (2011, 3.7e+06), (2012, 3.7e+06), (2013, 3.9e+06)

Desired_MWhs_of_demand_to_be_met_by_Solar_in_Base_Case =
Overall_Annual_MWh_Demand_from_SRP_CUstomers*Actual_Desired_Percentage_of_Demand_to_be_met_by_Solar

Desired_MWhs_of_demand_to_be_produced_Solar_in_Case_of_RS =
MWhs_of_demand_for_which_SRP_are_responsible_in_Case_of_RS*Actual_Desired_Percentage_of_Demand_to_be_met_by_Solar

Desired_MWs_of_Solar_in_Base_Case =
Desired_MWhs_of_demand_to_be_met_by_Solar_in_Base_Case*MWs_needed_tp_produce_1MWh_per_year_in_Arizona

Desired_MWs_of_Solar_in_case_of_RS =
Desired_MWhs_of_demand_to_be_produced_Solar_in_Case_of_RS*MWs_needed_tp_produce_1MWh_per_year_in_Arizona

Difference_between_MWs_of_Solar_With_RS_and_Without_RS =
Total_MWs_of_Solar_serving_SRP_customers_after_Rooftop_Solar-SRP_Solar_in_Base_Case

DIVERGING_Scenario_cost_Commercial_Solar_Relative_to_Residential =
GRAPH(TIME)
(2000, 0.802), (2001, 0.817), (2002, 0.831), (2003, 0.856), (2004, 0.871), (2005, 0.881), (2006, 0.86), (2007, 0.849), (2008, 0.903), (2009, 0.917), (2010, 0.867), (2011, 0.835), (2012, 0.806), (2013, 0.784), (2014, 0.777), (2015, 0.77), (2016, 0.766), (2017, 0.759), (2018, 0.755), (2019, 0.745), (2020, 0.734), (2021, 0.723), (2022, 0.719), (2023, 0.716), (2024, 0.712), (2025, 0.701), (2026, 0.698), (2027, 0.694), (2028, 0.687), (2029, 0.673), (2030, 0.662)

Diverging_Scenario_cost_Utility_Solar_relative_to_Residential = GRAPH(TIME)
(2000, 0.698), (2001, 0.683), (2002, 0.676), (2003, 0.676), (2004, 0.673), (2005, 0.669), (2006, 0.665), (2007, 0.665), (2008, 0.662), (2009, 0.655), (2010, 0.647), (2011, 0.619), (2012, 0.608), (2013, 0.597), (2014, 0.59), (2015, 0.572), (2016, 0.561), (2017, 0.55), (2018, 0.532), (2019, 0.522), (2020, 0.507), (2021, 0.496), (2022, 0.486), (2023, 0.478), (2024, 0.464), (2025, 0.457), (2026, 0.45), (2027, 0.446), (2028, 0.442), (2029, 0.428), (2030, 0.41)

Solar_Capacity_in_SRP's_service_area = GRAPH(TIME)
(2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 0.00), (2004, 0.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 25.3)

Rooftop solar_customers_as_a_fraction_of_all_customers = Rooftop_Solar_Adopters/SRP_Total_Customers
Roofotp solar_customers_as_a_fraction_of_potential_customers = Rooftop_Solar_Adopters/(Rooftop_Solar_Adopters+Potential_Rooftop_Solar_Adopters)

PV_Lifetime_1 = 25

Expected_Annual_Dollars_Saved_by_1MW_of__Rooftop_Solar_in_Arizona = IF TIME < Year_in_which_SRP_Special_Price_Plan_for_RS_Customers_is_enacted THEN Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona*Averaged_Expected_Rate_over__Rooftop_Solar_Investment*kWhs_per_MWh ELSE Averaged_Expected_Rate_over__Rooftop_Solar_Investment*Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona*kWhs_per_MWh - Annual_Increase_in_RS_Users_Bills_per_MW_due_to_new_rate_plan

Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona = 1730

Expected_Annual_MWhs_produced_per_MW_of_Solar_in_SRP_service_area_1 = 1730

Expected_Cost_of_1kWh_with_Rooftop solar = Overall_Perceived_Installed_Cost_per_MW_of_Rooftop_Solar/(Expected_Annual_MWhs_produced_per_MW_of_Solar_in_SRP_service_area_1*kWhs_per_MWh*PV_Lifetime_1)

Expected_kWh_demand_in_next_year = Overall_Annual_kWh_Demand_from_SRP_customers+Overall_Annual_kWh_Demand_from_SRP_customers*TREND(Overall_Annual_kWh_Demand_from_SRP_customers,4,0)

Expected_Payback_Period_of_Rooftop_Solar = MAX(Overall_Perceived_Installed_Cost_per_MW_of_Rooftop_Solar/Expected_Annual_Dollars_Saved_by_1MW_of__Rooftop_Solar_in_Arizona,0)

Expected_Profit_Lost_in_Next_Year_due_to_RS = Perceived_Annual_Profits_Lost_due_to_RS+SMTH1(Perceived_Annual_Profits_Lost_due_to_RS*TREND(Perceived_Annual_Profits_Lost_due_to_RS,3.5,0),5,0)

Expected_rate_20_years_in_the_future = SRP_Rates_per_kWh_after_Rooftop_Solar+

SRP_Rates_per_kWh_after_Rooftop_Solar*20*TREND(SRP_Rates_per_kWh_after_Rooftop_Solar,5,.02)

Fractional_reduction_in_RS_cost_per_year_HIGH = 0.06

Fractional_reduction_in_RS_cost_per_year_LOW = GRAPH(TIME)
(2000, 0.06), (2001, 0.06), (2002, 0.06), (2003, 0.06), (2004, 0.06), (2005, 0.06), (2006, 0.06), (2007, 0.06), (2008, 0.06), (2009, 0.06), (2010, 0.06), (2011, 0.06), (2012, 0.0518), (2013, 0.0453), (2014, 0.0381), (2015, 0.0338), (2016, 0.027), (2017, 0.0209), (2018, 0.0122), (2019, 0.00683), (2020, 0.000719), (2021, 0.000719), (2022, 0.00), (2023, 0.00), (2024, 0.00), (2025, 0.00), (2026, 0.00), (2027, 0.00), (2028, 0.00), (2029, 0.00), (2030, 0.00)

Fractional_reduction_in_RS_cost_per_year_MEDIUM = GRAPH(TIME)
(2000, 0.06), (2001, 0.06), (2002, 0.06), (2003, 0.06), (2004, 0.06), (2005, 0.06), (2006, 0.06), (2007, 0.06), (2008, 0.06), (2009, 0.06), (2010, 0.06), (2011, 0.06), (2012, 0.06), (2013, 0.0597), (2014, 0.0572), (2015, 0.0547), (2016, 0.0504), (2017, 0.0471), (2018, 0.0432), (2019, 0.041), (2020, 0.0371), (2021, 0.0331), (2022, 0.0306), (2023, 0.0284), (2024, 0.0252), (2025, 0.023), (2026, 0.0201), (2027, 0.0176), (2028, 0.0147), (2029, 0.0126), (2030, 0.00827)

Fraction_installing_Rooftop_Solar_per_year = GRAPH(Expected_Payback_Period_of_Rooftop_Solar/Willingness_to_Adopt)
(0.00, 1.00), (1.00, 0.495), (2.00, 0.399), (3.00, 0.327), (4.00, 0.253), (5.00, 0.203), (6.00, 0.146), (7.00, 0.1), (8.00, 0.06), (9.00, 0.04), (10.0, 0.03), (11.0, 0.02), (12.0, 0.015), (13.0, 0.013), (14.0, 0.01), (15.0, 0.008), (16.0, 0.007), (17.0, 0.006), (18.0, 0.005), (19.0, 0.004), (20.0, 0.003), (21.0, 0.0025), (22.0, 0.002), (23.0, 0.0016), (24.0, 0.0013), (25.0, 0.001), (26.0, 0.001), (27.0, 0.001), (28.0, 0.001), (29.0, 0.001), (30.0, 0.001), (31.0, 0.00), (32.0, 0.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 0.00), (37.0, 0.00), (38.0, 0.00), (39.0, 0.00), (40.0, 0.00), (41.0, 0.00), (42.0, 0.00), (43.0, 0.00), (44.0, 0.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 0.00), (50.0, 0.00)

Fraction_of_Arizona_Customers_that_are_SRP_Customers = 0.33

Fraction_of_Demand_over_which_lost_profits_from_RS_are_spread = 0.44

Fraction_of_Rooftop_Solar_Systems_from_which_SRP_receives_RECS = 1

Fraction_of_RPS_Target_that_would_be_achieved_by_SRP_without_RS = 1

Fraction_of_SRP_Residential_Customers_using_Time_of_Day_rate_plan = 0.4

Fraction_that_are_Commercial_Customers = 0.1

Fraction_that_are_Residential_Customers = 0.89

Fuel_Costs_per_MWh_of_Coal_Energy = GRAPH(TIME)
(2000, 17.3), (2001, 17.3), (2002, 17.3), (2003, 17.3), (2004, 18.2), (2005, 21.7), (2006, 23.1), (2007, 23.9), (2008, 28.4), (2009, 32.3), (2010, 27.7), (2011, 27.1), (2012, 28.3), (2013, 28.3)

Fuel_costs_per_MWH_of_Nuclear_Energy = GRAPH(TIME)
(2000, 4.60), (2001, 4.60), (2002, 4.60), (2003, 4.60), (2004, 4.58), (2005, 4.63), (2006, 4.85), (2007, 4.99), (2008, 5.29), (2009, 5.35), (2010, 6.68), (2011, 7.01), (2012, 7.61), (2013, 7.61)

Future_Investments_in_capacity = Normal_future_investments_in_capacity-1
Growth_in_SRP_MWh_demand_per_year = 0.01

Growth_rate_of_Arizona_Electric_customers = IF TIME < 2013 THEN

Historical_Growth_rate_of_Arizona_Electric_Customers ELSE

Projected_Annual_Growth_Rate_of_Arizona_Electric_Customers

Historical_and_Projected_Installed_Cost_per_MW_Commercial_Solar = IF Scenario_CONVERGING_DIVERGING_or_NO_CHANGE_for_relative_cost_Comm = 1 THEN Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*CONVERGING_Scenario_cost_Commercial_Solar_relative_to_Residential ELSE IF Scenario_CONVERGING_DIVERGING_or_NO_CHANGE_for_relative_cost_Comm = 0 THEN Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*NO_CHANGE_Scenario_cost_Commercial_Solar_relative_to_Residential ELSE Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*DIVERGING_Scenario_cost_Commercial_Solar_Relative_to_Residential

Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar = IF TIME > 2012 THEN Projected_Installed_cost_per_MW_of_Residential_Solar ELSE Historical_Installed_Cost_per_MW_of_Residential_solar

Historical_Annual_MWh_demand = GRAPH(TIME)
(2000, 2.9e+07), (2001, 2.9e+07), (2002, 3e+07), (2003, 3e+07), (2004, 3e+07), (2005, 3e+07), (2006, 3.1e+07), (2007, 3.2e+07), (2008, 3.2e+07), (2009,

3.3e+07), (2010, 3.3e+07), (2011, 3.2e+07), (2012, 3.1e+07), (2013, 3.2e+07), (2014, 3.4e+07)

Historical_Growth_rate_of_Arizona_Electric_Customers = 0.022

Historical_Installed_Cost_per_MW_of_Residential_solar = GRAPH(TIME)
(2000, 1.2e+07), (2001, 1.1e+07), (2002, 1e+07), (2003, 1e+07), (2004, 1e+07), (2005, 9.3e+06), (2006, 9e+06), (2006, 8.4e+06), (2007, 7.9e+06), (2008, 7.6e+06), (2009, 7.6e+06), (2010, 7e+06), (2011, 6.5e+06), (2012, 5.4e+06)

Historical_Revenues_receieved = GRAPH(TIME)
(2000, 2.6e+09), (2001, 2.6e+09), (2002, 2.6e+09), (2003, 2.6e+09), (2004, 2.6e+09), (2005, 2.6e+09), (2006, 2.6e+09), (2007, 2.6e+09), (2008, 2.6e+09), (2009, 2.6e+09), (2010, 2.6e+09), (2011, 2.6e+09), (2012, 2.6e+09), (2013, 2.6e+09)

Historical_Tax_Credit_to_2016 = GRAPH(TIME)
(2000, 0.00), (2000, 0.00), (2000, 0.00), (2001, 0.00), (2001, 0.00), (2001, 0.00), (2002, 0.00), (2002, 0.00), (2002, 0.00), (2002, 0.00), (2002, 0.00), (2003, 0.00), (2003, 0.00), (2003, 0.00), (2004, 0.00), (2004, 0.00), (2004, 0.00), (2004, 0.00), (2004, 0.00), (2005, 0.00), (2005, 0.00), (2005, 0.00), (2006, 0.00), (2006, 0.00), (2006, 0.3), (2006, 0.3), (2006, 0.3), (2007, 0.3), (2007, 0.3), (2007, 0.3), (2008, 0.3), (2008, 0.3), (2008, 0.3), (2008, 0.3), (2008, 0.3), (2009, 0.3), (2009, 0.3), (2009, 0.3), (2010, 0.3), (2010, 0.3), (2010, 0.3), (2010, 0.3), (2010, 0.3), (2011, 0.3), (2011, 0.3), (2011, 0.3), (2012, 0.3), (2012, 0.3), (2012, 0.3), (2012, 0.3), (2012, 0.3), (2013, 0.3), (2013, 0.3), (2013, 0.3), (2014, 0.3), (2014, 0.3), (2014, 0.3), (2014, 0.3), (2014, 0.3), (2015, 0.3), (2015, 0.3), (2015, 0.3), (2016, 0.3), (2016, 0.3), (2016, 0.00), (2016, 0.00), (2016, 0.00), (2017, 0.00), (2017, 0.00)

Historic_and_Projected_Installed_Cost_Per_MW_Utility_Scale_Solar = IF Scenario_CONVERGING_DIVERGING_or_NO_CHANGE_for_relative_cost_Util = 1 THEN Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*CONVERGING_Scenario_cost_Utility_Solar_relative_to_Residential ELSE IF

Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar = 0 THEN Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*NO_Change_Scenario_cost_Utility_Solar_relative_to_Residential ELSE Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*Diverging_Scenario_cost_Utility_Solar_relative_to_Residential

Historic_Variable_costs_per_MWh_of_Natural_Gas_Plant_Electricity = GRAPH(TIME)

(2000, 33.9), (2001, 37.3), (2002, 39.3), (2003, 49.7), (2004, 51.6), (2005, 61.1), (2006, 59.6), (2007, 64.4), (2008, 70.7), (2009, 57.5), (2010, 48.7), (2011, 44.5), (2012, 35.7)

Industrial_Customers = 0.01

Interest_Rate = 0.01

Intermittency_and_Reduction_in_Control_Costs = 0

kWhs_per_MWh = 1000

Loss_Factor = 0

Million_Tons_of_CO2_emissions_per_MWh_of_Natural_Gas_electricity = 6e-07

MWhs_of_demand_for_which_SRP_are_responsible_in_Case_of_RS = Overall_Annual_MWh_Demand_from_SRP_CUstomers-Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems*(1-Fraction_of_Rooftop_Solar_Systems_from_which_SRP_receives_RECS)

MWs_needed_tp_produce_1MWh_per_year_in_Arizona = 0.0005780347

Normal_future_investments_in_capacity = 1000

NO_CHANGE_Scenario_cost_Commercial_Solar_relative_to_Residential = GRAPH(TIME)
(2000, 0.802), (2001, 0.817), (2002, 0.831), (2003, 0.856), (2004, 0.871), (2005, 0.881), (2006, 0.86), (2007, 0.849), (2008, 0.903), (2009, 0.917), (2010, 0.867), (2011, 0.835), (2012, 0.806), (2013, 0.806), (2014, 0.806), (2015, 0.806), (2016, 0.806), (2017, 0.806), (2018, 0.806), (2019, 0.806), (2020, 0.806), (2021, 0.806), (2022, 0.806), (2023, 0.806), (2024, 0.806), (2025, 0.806), (2026, 0.806), (2027, 0.806), (2028, 0.806), (2029, 0.806), (2030, 0.806)

NO_Change_Scenario_cost_Utility_Solar_relative_to_Residential = GRAPH(TIME)
(2000, 0.698), (2001, 0.683), (2002, 0.676), (2003, 0.676), (2004, 0.673), (2005, 0.669), (2006, 0.665), (2007, 0.665), (2008, 0.662), (2009, 0.655), (2010, 0.647), (2011, 0.63), (2012, 0.622), (2013, 0.615), (2014, 0.615), (2015, 0.615), (2016, 0.619), (2017, 0.622), (2018, 0.622), (2019, 0.622), (2020, 0.622), (2021, 0.622), (2022, 0.622), (2023, 0.622), (2024, 0.622), (2025, 0.622), (2026, 0.622), (2027, 0.622), (2028, 0.622), (2029, 0.622), (2030, 0.622)

Operating_and_Maintenance_Cost_per_MWh_with_Nuclear = GRAPH(TIME)

(2000, 18.9), (2001, 18.9), (2002, 18.9), (2003, 18.9), (2004, 18.9), (2005, 18.1), (2006, 19.6), (2007, 20.3), (2008, 21.4), (2009, 21.7), (2010, 24.0), (2011, 24.7), (2012, 27.4), (2013, 27.4)

Operating_and_Maintenance_Cost_per_MWh_with_with_Coal = GRAPH(TIME)
(2000, 22.8), (2001, 22.8), (2002, 22.8), (2003, 22.8), (2004, 24.3), (2005, 27.9), (2006, 29.9), (2007, 30.9), (2008, 35.8), (2009, 40.5), (2010, 35.8), (2011, 35.1), (2012, 37.2), (2013, 37.2)

Operating_Expenses = GRAPH(TIME)
(2000, 2.7e+09), (2001, 2.7e+09), (2002, 2.7e+09), (2003, 2.7e+09), (2004, 2.7e+09), (2005, 2.7e+09), (2006, 2.7e+09), (2007, 2.7e+09), (2008, 2.7e+09), (2009, 2.7e+09), (2010, 2.7e+09), (2011, 2.7e+09), (2012, 2.7e+09), (2013, 2.7e+09)

Overall_Annual_kWh_Demand_from_SRP_customers = Overall_Annual_MWh_Demand_from_SRP_CUstomers*kWhs_per_MWh

Overall_Annual_MWh_Demand_from_SRP_CUstomers = IF TIME > 2014 THEN Projected_Annual_MWh_demand ELSE Historical_Annual_MWh_demand

Overall_Perceived_Installed_Cost_per_MW_of_Rooftop_Solar = Historical_and_Projected_Installed_Cost_per_MW_Residential_Solar*(1-Tax_Credit_for_Residential_Solar)*(1-Accumulated_MWs_of_Rooftop_Solar_Installed*Percentage_Cost_Savings_per_MW_of_Rooftop_Solar_Installed)

Perceived_Investments_needed_after_Rooftop_Solar = Desired_MWs_of_Solar_in_case_of_RS-(SRP_Solar_after_Rooftop_Solar+MWs_of_Rooftop_Solar_from_which_SRP_claim_RECs)

Perceived_Investments_needed_in_Base_Case = Desired_MWs_of_Solar_in_Base_Case-SRP_Solar_in_Base_Case

Percentage_Cost_Savings_per_MW_of_Rooftop_Solar_Installed = IF TIME > 2012 THEN 3.875e-05 ELSE 0

Percentage_of_Demand_met_by_Rooftop_Solar = Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems/Overall_Annual_MWh_Demand_from_SRP_CUstomers

Percentage_of_Demand_that_comes_from_Residential_Customers = 0.44

Price_of_RECs_to_claim_1MWh_of_Solar_Output = 45

Projected_Annual_Growth_Rate_of_Arizona_Electric_Customers = 0.022
Rate_in_Dollars_per_Kwh =
Required_revenues/(Historical_Annual_MWh_demand*kWhs_per_MWh)

Rate_of_Return = 1

Ratio_of_Demand_in_Peak_Sun_hours_to_demand_in_offpeak_Sun_hours = 0

Ratio_of_West_to_South_Facing_Panels = 1

Required_revenues =
(SRP_Net_Plant_in_Service*Rate_of_Return)+Operating_Expenses

RS_On_OFF_Switch = 1

Scenario_CONVERGING_DIVERGING_or_NO_CHANGE_for_relative_cost_Comm = 0

Scenario_CONVERGING_DIVERGING_or_NO_CHANGE_for_relative_cost_Util = 0

SCENARIO_Goal_as_an_Expoenential_Progression = GRAPH(TIME)
(2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 0.00), (2004, 0.00), (2005, 0.00), (2006, 0.000356), (2007, 0.000712), (2008, 0.000712), (2009, 0.00214), (2010, 0.00427), (2011, 0.00783), (2012, 0.0135), (2013, 0.0199), (2014, 0.0249), (2015, 0.0313), (2016, 0.037), (2017, 0.0456), (2018, 0.0569), (2019, 0.0676), (2020, 0.0811), (2021, 0.0947), (2022, 0.11), (2023, 0.126), (2024, 0.141), (2025, 0.154), (2026, 0.174), (2027, 0.183), (2028, 0.189), (2029, 0.195), (2030, 0.198)

SCENARIO_Goal_as_a_Linear_Progression = GRAPH(TIME)
(2000, 0.00), (2010, 0.065), (2020, 0.13), (2030, 0.2)

SCENARIO_HIGH_MEDIUM_or_LOW_Cost_Reductions_for_Residential_Solar = 0

SCENARIO_HIGH_MED_LOW_SRP_RATES_GROWTH_RATE = 0

SCENARIO_Natural_Gas_Variable_Costs_Growth_Rates = 0

SCENARIO_On_means_LINEAR_Off_Means_EXPONENTIAL = 2

Solar_Panels_in_SRP's_Service_Area = GRAPH(TIME)

(2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 0.00), (2004, 0.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 315)

SRP's_Generation_Percentages[Coal] = .55

SRP's_Generation_Percentages[Nuclear] = .19

SRP's_Generation_Percentages[Gas_Wind_Solar] = .22

SRPs_Solar_Renewable_Portfolio_Standards_for_each_year = IF

SCENARIO_On_means_LINEAR_Off_Means_EXPONENTIAL = 1 THEN

SCENARIO_Goal_as_a_Linear_Progression ELSE

SCENARIO_Goal_as_an_Expoenential_Progression

SRP_Commercial_Customers =

SRP_Total_Customers*Fraction_that_are_Commercial_Customers

SRP_Money_Spent_per_Year_on_RECs = MWs_of_Rooftop_Solar_from_which_SRP_claim_RECs*Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona*Price_of_RECs_to_claim_1MWh_of_Solar_Output

SRP_Net_Plant_in_Service = GRAPH(TIME)
(2000, 3.4e+09), (2001, 7.4e+09), (2002, 7.4e+09), (2003, 7.4e+09), (2004, 7.4e+09), (2005, 7.4e+09), (2006, 7.4e+09), (2007, 7.4e+09), (2008, 7.4e+09), (2009, 7.4e+09), (2010, 7.4e+09), (2011, 7.4e+09), (2012, 7.4e+09), (2013, 7.4e+09)

SRP_Rates_per_kWh_after_Rooftop_Solar = IF TIME > 2013 THEN SRP_Rates_per_kWh_in_Base_Case + Annual_Addition_in_Rates_due_to_Rooftop_Solar ELSE SRP_Rates_per_kWh_in_Base_Case

SRP_Rates_per_kWh_in_Base_Case = IF TIME > 2013 THEN Projected_Normal_SRP_Rates_per_kWh ELSE DATA_Average_Residential_Rates_in_Arizona

SRP_Residential_Customers = SRP_Total_Customers*Fraction_that_are_Residential_Customers
SRP_Total_Customers = Arizona_Electric_Customers*Fraction_of_Arizona_customers_that_are_SRP_Customers

Tax_Credit_for_Residential_Solar = IF TIME < 2016 THEN Historical_Tax_Credit_to_2016 ELSE Tax_credit_post_2016

Tax_credit_post_2016 = 0

Time_for_SRP_managers_to_Perceive_RS Installations = 1

Time_for_SRP_Solar_Installations = 1

Time_to_Install_Rooftop_Solar = 1

Time_to_Perceive_Money_Lost = 1

Total_Annual_Costs_Avoided_due_to_Rooftop_Solar = Annual_SRP_Variable_Costs_Avoided_due_to_Rooftop_Solar+Annual_SRP_Capacity_Investment_Costs_Avoided_due_to_RS

Total_Annual_MWhs_Produced_by_Rooftop_Solar_Systems = Accumulated_MWs_of_Rooftop_Solar_Installed*Expected_Annual_MWhs_produced_per_MW_of_Solar_in_Arizona

Total_MWs_of_Solar_serving_SRP_customers_after_Rooftop_Solar = Accumulated_MWs_of_Rooftop_Solar_Installed+SRP_Solar_after_Rooftop_Solar

Transmission_&_Distribution_Losses = 1

Variable_Costs_per_MWh_Natural_Gas_Electricity = IF TIME > 2012 THEN Projected_Variable_Costs_per_MWh_Natural_Gas_Electricity ELSE Historic_Variable_costs_per_MWh_of_Natural_Gas_Plant_Electricity

Variable_costs_per_MWh_produced_by_SRP[Demand_Times] = 100

Willingness_to_Adopt = 1

WOM_Effect = IF Expected_Payback_Period_of_Rooftop_Solar <25 THEN (Potential_Rooftop_Solar_Adopters*Rooftop_Solar_Adopters*Contact_Rate*Adop tion_from_WOM_Fraction)/(Potential_Rooftop_Solar_Adopters+Rooftop_Solar_Adopters) ELSE 0

Years_between_RS_Installation_and_Receiving_Contract_for_RECs = 1

Year_in_which_SRP_Special_Price_Plan_for_RS_Customers_is_enacted = 2015

Appendix B – Justifications of the estimated values used in the model

1. Estimation of the **initial value for the stock of rooftop solar adopters in SRP's service:**

This data could not be obtained directly, and so the estimation was formed as follows:

We know that SRP serves 983,745 electric customers [84].

We know that Arizona had 2,947,070 total electric retail customers in 2013 [85].

Thus we can say that SRP serves roughly 983745/2947070 = .333, or roughly 33% of Arizona's retail electric customers.

We also know that the number of electric customers in Arizona has been growing at about 2.2% per year [68]. If SRP's customer base has been growing at a similar rate, then we can say that in 2000 it had roughly 723824 customers (calculated through regression).

But how many of these customers were potential rooftop solar customers? Well, since in this model we are only looking at residential customers and since we also know that in Arizona roughly 89% of electric customers are residential customers, we can say that SRP was serving 723824*.89 =
644204 residential customers. See side calculations in the model for more details.

But how many of these customers could actually install rooftop solar? Those who live in apartments are generally not able to do so. So let us say that only households can install rooftop solar. But how many households does SRP serve?

This information was unavailable, both for SRP and for Arizona at large. As such at this point we must make an educated guess. This guess can be aided by the knowledge that the homeownership rate in Arizona is 64.4% [85]. This rate includes apartments and other forms of accommodation not suitable to rooftop solar, and so finally we can estimate that if 3/4 of the people who own property in Arizona own a home suitable for rooftop solar, then roughly 48.3% of Arizona's (and by proxy SRP's) residential electric customer base would be candidates for rooftop solar. This translates into the following number of potential rooftop solar adopters in SRP's service area in the year 2000: 644203*.483 = 311150 residential electric customers who could potentially install rooftop solar.

2. Estimation of **Percentage Cost Savings per MW of Rooftop Solar Installed:**

The technological learning curve of Solar is an even more important factor in its declining cost. Solar has been known to show signs of a particularly impressive learning curve. An idea known as 'Swanson's law' states that, based on historical observations, the price per watt of PV solar 'falls by 20% with each doubling of global manufacturing capacity' [86]

However on this model we are not dealing with solar on a global scale. The increase in production in this model, where production occurs only for a small part of one U.S. state, is likely to have very little effect on the installed cost per MW of solar. This explains why the number for this variable is so low. It was included in the model so as to draw the user's awareness to the importance of the learning curve of solar, and how this will likely reinforce its diffusion. However under this value it has little quantitative effect on the model simulations.

The number for this variable was determined as follows:

In a solar pricing report conducted by the International Renewable Energy Agency, it was revealed that between 2010 and 2014, the global module average selling price of solar fell from $1.52 per peak watt to $1.05 per peak watt [10]. This shows a reduction of roughly 31%. Accompanying this price reduction, there was an increase in installations of roughly 8000MWs. If we take this 31% reduction as indicative of the learning curve of solar (which the graph in this study does) then we can say that the cost reduction per MW of solar between the years of 2010 and 2014 was:

31/8000 = .003875 percent cost reduction per MW of solar installed.

We can test this logic by saying that if 8000MWs per installed, then the percentile reduction in cost should be:

8000*.00003875= .31, i.e. a 31% cost reduction, which is indeed what we saw in the graph over the 2010 to 2014 period.

This data is based on selling price, and so should also account for not only the learning curve for 'hard costs' such as module prices, but also for the learning curve for the 'soft costs' such as the administration and installation that also affect the selling price of solar.