Appendix

Appendix A. Spatial Distribution of PV Systems in Germany

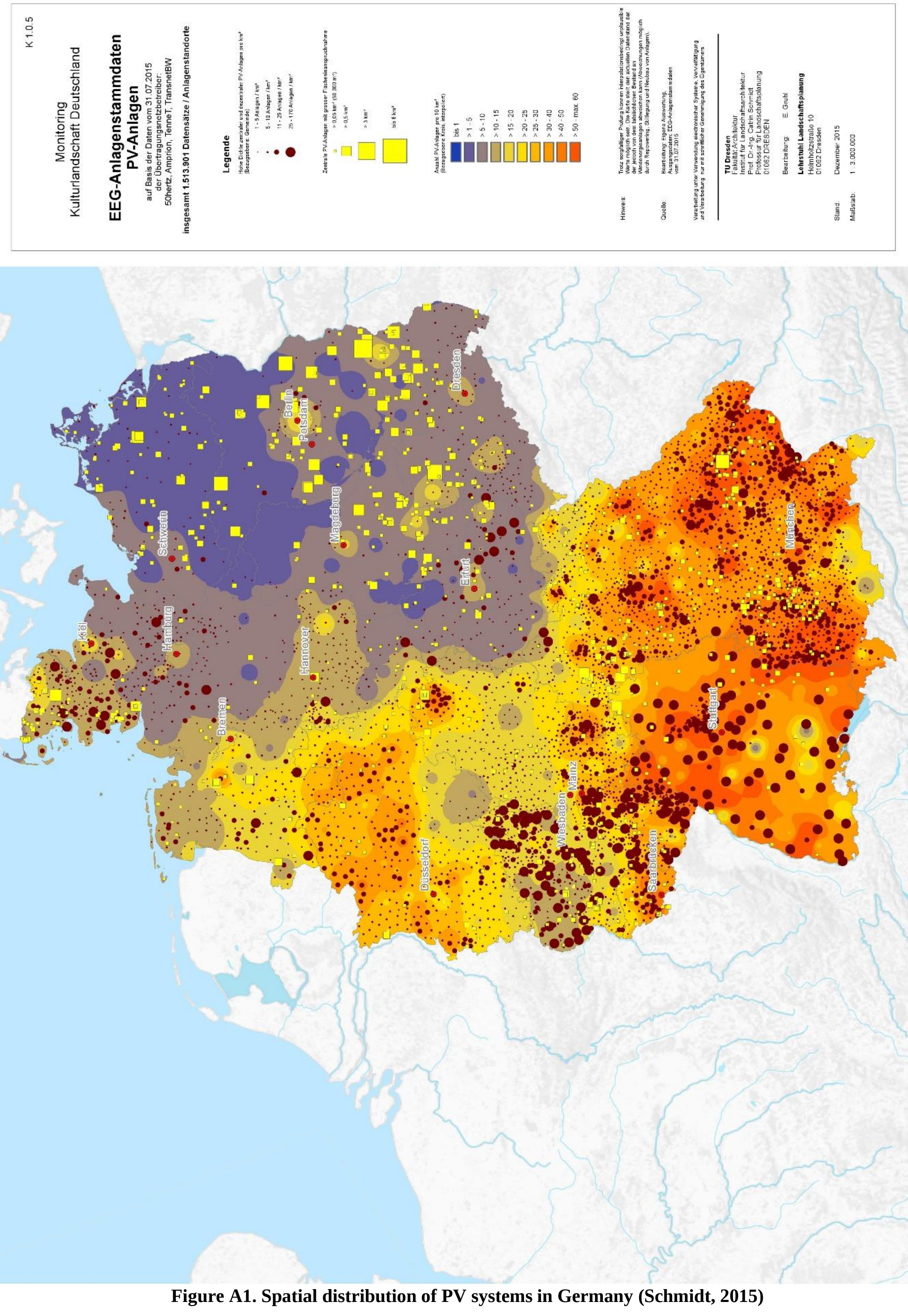

Figure A1. Spatial distribution of PV systems in Germany (Schmidt, 2015)

Appendix B. Full Model and Legend of Variable Types

Color	Variable Type
	Endogenous variables as determined by the dynamics of the system
	Exogenous input (e.g. real data)
	Initial input values at the start of the simulation (=2002)
	Shadow variables which are determined elsewhere in order to prevent clutter and overlaps
	Historical data which simulated variables are compared to
	Constant parameters representing information delays (e.g. time adjustments)
	Variables changed for scenario analysis
	Switches used for scenario analysis

Table A1. Legend of variable types

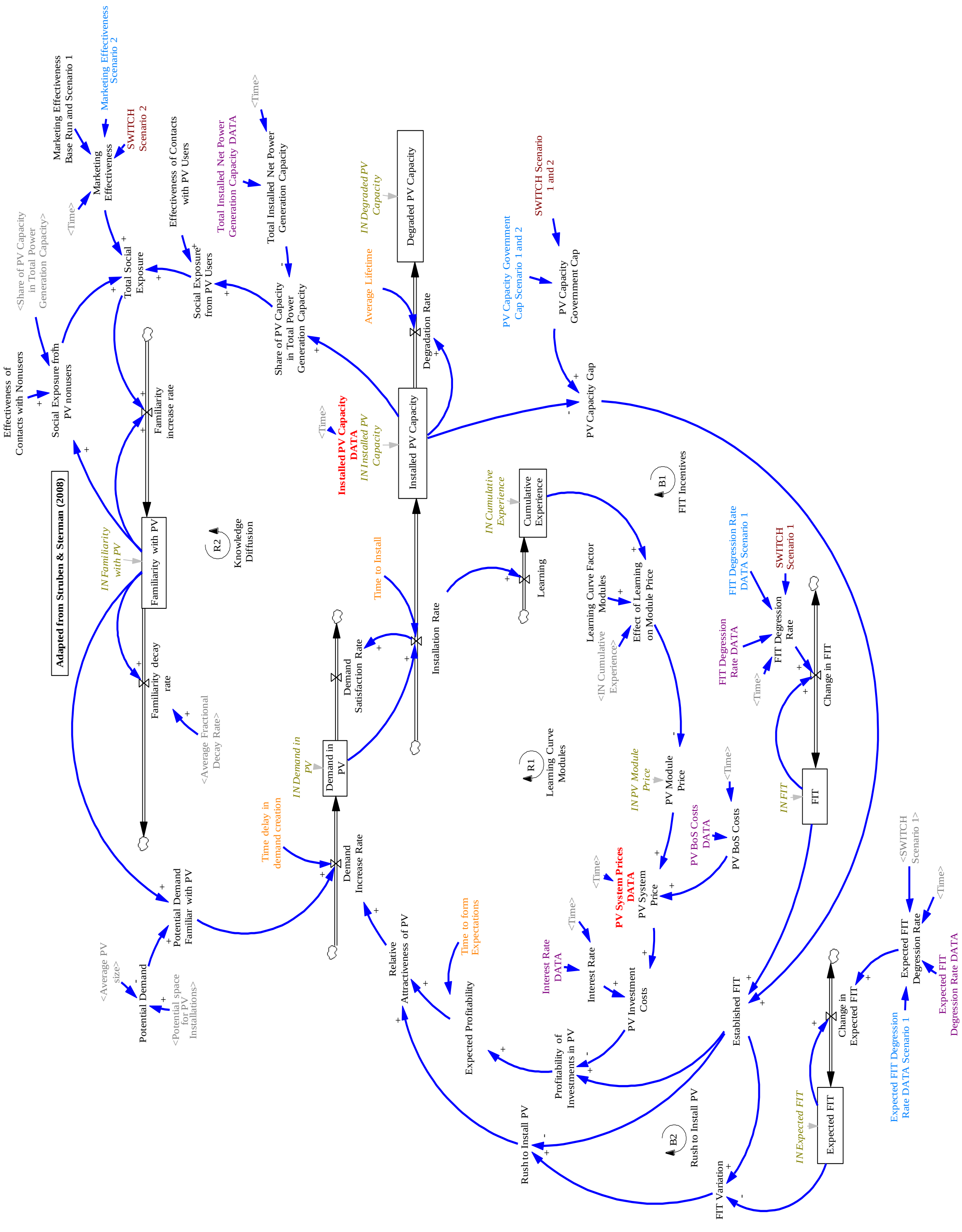

Figure A2. Full model in large-scale

Appendix C. General Simulation Settings

The simulation model was implemented in Vensim PLE, Version 7.3.5 Single Precision (x32) for Windows. Model settings are described below (Table A2).

Initial Time	2002
Final Time	2018
Time Step	0.125
Units for Time	Year
Integration Type	Euler

Table A2. General simulation settings in Vensim PLE

Appendix D. Experimental Runs Settings

	Base Run	**Scenario 1: Harmonized FIT Degression Rates**	**Scenario 2: PV Awareness Programmes**
Description		FIT degression rates are harmonized and implemented stepwise.	More awareness campaigns are launched.
SWITCH 'FIT Scenario 1' 0 = Actual FIT degression rates 1 = Harmonized FIT degression rates as of 2019 at 0.05	0	1	0
SWITCH 'Scenario 2' 0 = Actual marketing effectiveness of 0.01 1 = Aggressive marketing effectiveness of 0.025 as of 2006.	0	0	1
SWITCH 'Scenario 1 and 2' 0 = Official PV Cap of 52 GWp 1 = Extended PV Cap of 120 GWp	0	1	1

Table A3. Model experimental runs settings

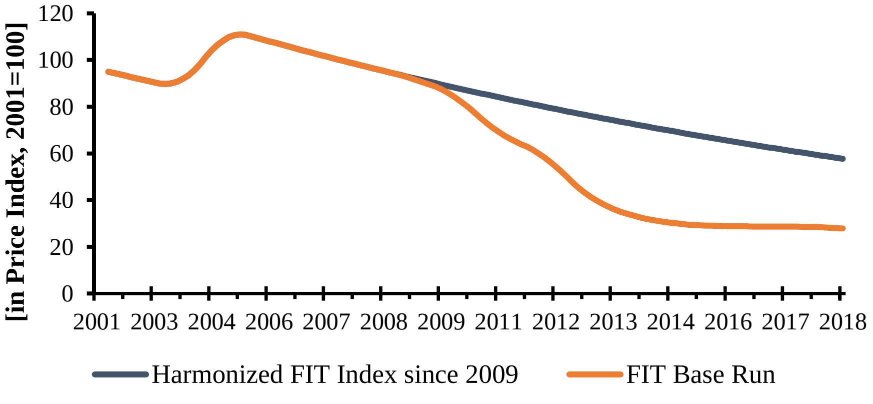

Figure A3. Scenario 1: Comparison of FIT

Appendix E. Equations

	Equations and Comments	Units
(1)	Average Fractional Decay Rate = (Maximum decay rate*((EXP(((-4*Slope of decay rate))*(Total Social Exposure-Reference Rate of Social Exposure))))/(1+(EXP((-4*Slope of decay rate)*(Total Social Exposure-Reference Rate of Social Exposure))))) This is the average fractional rate at which the familiarity with PV decays. Adopted from Struben and Sterman (2008).	1/year
(2)	Average Lifetime = 20 This the value for the average lifetime of a PV system. It is assumed to be similar to the period, where FITs are paid. It is assumed that PV capacity is not used anymore after 20 years.	year
(3)	Average PV size = 9e-06 This is the average space in km² that is needed to install a PV capacity of 1 kWp. Source: Lödl et al. (2010) and Eisert (2012)	km²/ kWp
(4)	Change in Expected FIT = Expected FIT Degression Rate*Expected FIT This flow adjusts the expected FIT. Since degression rates are publicly available and announced in advance, it is assumed that they can be accurately estimated.	Price index/ year
(5)	Change in FIT = FIT Degression Rate * FIT This flow changes the stock of FIT paid for fed-in PV electricity.	Price Index /year
(6)	Change in Potential PV Space = (Degradation Rate-Installation Rate)*Average PV size This flow adjusts the potential space for PV installations. It is assumed that degraded PV systems become potential space and hence potential demand again.	km²/ year
(7)	Cumulative Experience = INTEG(Learning, IN Cumulative Experience) This variable represents the cumulative experience from installing PV systems. The experience is proxied by the cumulative production. It is adjusted by the installation rate but has no outflow since it is assumed that the experience does not decrease.	kWp
(8)	Degradation Rate = Installed PV Capacity/Average Lifetime The outflow adjusts the stock Installed PV capacity since PV systems have a limited lifetime.	kWp/ year
(9)	Degraded PV Capacity = INTEG(Degradation Rate, IN Degraded PV Capacity) This stock accumulates the degraded PV capacity which is demolished after 20 years.	kWp
(10)	Demand in PV = INTEG(Demand Increase Rate – Demand Satisfaction Rate; IN Demand in PV) This is the stock that accumulates demand for PV, i.e. how many kWp are demanded in total at a certain point of time.	kWp
(11)	Demand Increase Rate = MAX((Potential Demand Familiar with PV*Relative Attractiveness of PV)/ Time delay in demand creation , 0) This is the growth rate of PV demand, where it is assumed that there is no negative demand for PV. The incorporated smooth function adjusts for the time delay because people do not react to changes in attractivity factors immediately.	kWp/ year
(12)	Demand Satisfaction Rate = Installation Rate The demand satisfaction rate decreases the demand according to the installation rate, i.e. when PV systems are built.	kWp/ year
(13)	Effect of Learning on Module Price = (Cumulative Experience/IN Cumulative Experience)^Learning Curve Factor Modules This represents the learning effect that comes with increased experience in producing modules. The effect of learning on price includes increases in effectiveness, new innovations and other factors such as streamlining.	Dmnl
(14)	Effectiveness of Contacts with PV Users = 0.25 This represents the effectiveness of social exposure coming from PV users.	1/year
(15)	Effectiveness of Contacts with Nonusers = 0.125 This represents the effectiveness of social exposure or learning coming from non-PV-users. It is assumed to be half the effectiveness of contacts with PV users.	1/year
(16)	Established FIT= IF THEN ELSE(PV Capacity Gap>0,FIT,0) This variable returns the established FIT, taking into account the constraints set by the PV government cap. If the installed capacity exceeds the PV cap, no FIT will be paid.	Price index
(17)	Expected FIT = INTEG(Change in Expected FIT, IN Expected FIT) This stock variable represents the future subsidy value with one year in advance (i.e. the expected FIT becomes the established FIT after 1 year). It is expected that people can accurately estimate the FIT as degression rates are published.	Price index
(18)	Expected FIT Degression Rate = IF THEN ELSE(SWITCH Scenario 1 = 0, Expected FIT Degression Rate DATA(Time), Expected FIT Degression Rate DATA Scenario 1(Time)) This function returns the value of the expected degression rate from 2002 to 2018 in the base run, i.e. real data and in one hypothetical scenario. The degression rate equals the future established FIT degression rate with one year in advance.	1/year
(19)	Expected FIT Degression Rate DATA [(2002,-0.4)-(2018,0.4)],(2002,-0.0499),(2003,0.256), (2004,-0.05),(2005,-0.05),(2006,-0.05),(2007,-0.05), (2008,-0.08),(2009,-0.232),(2010,-0.1299),(2011,-0.3928), (2012,-0.2046),(2013,-0.0929),(2014,-0.0222),(2015,0),(2016,-0.0089),(2017,-0.05),(2018,-0.1217)	1/year

	This is the exogenous input for the expected FIT degression rate from 2002 to 2018.For simplicity, it is assumed that the FIT is only adjusted once a year. However, in reality, starting from 2009 the FIT was adjusted in higher iterations. The input reflects the actual future FIT degression rate with one year in advance. Data source: Netztransparenz (2019)	
(20)	Expected FIT Degression Rate DATA Scenario 1 [(2002,-0.4)-(2018,0.4)],(2002,-0.0499), (2003,0.256),(2004,-0.05),(2005,-0.05),(2006,-0.05) ,(2007,-0.05),(2008,-0.05),(2009,-0.05), ,(2010,-0.05),(2011,-0.05),(2012,-0.05),(2013,-0.05), (2014,-0.05),(2015,-0.05),(2016,-0.05) ,(2017,-0.05),(2018,-0.05) This lookup entails the exogenous input for the FIT degression rate in scenario 1. The input reflects the actual future FIT degression rate with one year in advance.	1/year
(21)	Expected Profitability = SMOOTH(Profitability of Investments in PV, Time to form Expectations) The value returns the expected profitability of investments in PV that is delayed by the time to realise the new profitability.	Dmnl
(22)	Familiarity decay rate = Average Fractional Decay Rate*Familiarity with PV This outflow adjusts for the decay of familiarity over time, i.e. when there is not enough social exposure to maintain current familiarity. It takes some effort and attention to remain up to date with the status quo of PV systems and features. Hence, familiarity erodes over time unless refreshed through social exposure. The decay is non-linear because the greater the exposure, the slower the decay. Similarly, the lower the exposure, the faster the decay and vice versa.	Dmnl/ year
(23)	Familiarity increase rate = Total Social Exposure*(1-Familiarity with PV) This inflow adjusts for the increase in PV familiarity. It includes the total social exposure from three different sources and the fraction that is unfamiliar with PV.	Dmnl/ year
(24)	Familiarity with PV = INTEG(Familiarity increase rate-Familiarity decay rate, IN Familiarity with PV) This stock represents the current degree of familiarity with PV among the population. Familiarity ranges between 0 and 1, where 0 represents no familiarity with PV and 1 indicates that all potential adopters are familiar with PV. The stock variable is adjusted for gains and decay in familiarity.	Dmnl
(25)	FIT = INTEG(Change in FIT, IN FIT) This is the guaranteed Feed-In Tariff for feeding PV electricity into the electricity grid. As set by the government, once the PV Cap of installed PV capacity is reached, the FIT will be abolished.	Price index
(26)	FIT Degression Rate = IF THEN ELSE(SWITCH Scenario 1 = 0, FIT Degression Rate DATA(Time), FIT Degression Rate DATA Scenario 1(Time)) This function returns the value of the degression rate from 2002 to 2018 in the base run, i.e. real historical data and the degression rates for one hypothetical scenario.	1/year
(27)	FIT Degression Rate DATA [(2002,-0.4)-(2018,0.4)],(2002,-0.0498), (2003,-0.0499),(2004,0.256),(2005,-0.05),(2006,-0.05),(2007,-0.05),(2008,-0.05), (2009,-0.08),(2010,-0.232),(2011,-0.1299) ,(2012,-0.3928),(2013,-0.2046),(2014,-0.0929),(2015,-0.0222),(2016,0),(2017,-0.0089),(2018,-0.05) This is the exogenous input for the FIT degression rate from 2002 to 2018.For simplicity, it is assumed that the FIT has only been adjusted once a year. However, in reality, starting from 2012 the FIT was adjusted in higher iterations. The degression rates were retrieved from Netztransparenz (2019).	1/year
(28)	FIT Degression Rate DATA Scenario 1 [(2002,-0.4)-(2018,0.4)],(2002,-0.0498),(2003,-0.0499) ,(2004,0.256),(2005,-0.05),(2006,-0.05),(2007,-0.05), (2008,-0.05),(2009,-0.05),(2010,-0.05),(2011,-0.05) ,(2012,-0.05),(2013,-0.05),(2014,-0.05),(2015,-0.05), (2016,-0.05),(2017,-0.05),(2018,-0.05) This is the lookup for the FIT degression rate in scenario 1. It assumes that the degression rates would not have been cut as hastily and rapidly but instead harmonised at five percent.	1/year
(29)	FIT Variation = Established FIT-Expected FIT This variable captures the difference between the established FIT and the anticipated FIT. A positive FIT Variation indicates that the Established FIT exceeds the Expected FIT at a certain point in time. Hence, a positive variation indicates that the FIT will be lowered.	Price index
(30)	IN Degraded PV Capacity = 1000 This is the assumed initial value of the Degraded PV capacity at the start of the simulation.	kWp
(31)	IN Demand in PV = INITIAL(22500) This is the initial value of demand at the start of the simulation.	kWp
(32)	IN Expected FIT = INITIAL(90.28) This is the initial expected FIT. It is set to be 90.28 which equals the future established FIT in one year. Data source: Netztransparenz (2019).	Price index
(33)	IN Familiarity with PV = INITIAL(0.02) This is the initial value for the familiarity with PV. It is assumed to be very low at the beginning of the simulation, since PV constituted a relatively new, unknown and not widespread technology in 2002.	Dmnl
(34)	IN FIT = 95.02 This is the initial indexed feed-in tariff at the start of the simulation (2002). It is initialised at 2001, where the FIT was introduced. Data source: Netztransparenz (2019).	Price index
(35)	IN Installed PV capacity = INITIAL(296*10^3) This is the initial value for the installed capacity at the start of the simulation (year = 2002). Data source: BMWi (2019b).	kWp
(36)	IN Potential space for installation = IN rooftop potential*Average PV size	km²

	This is the initial value for the potential PV space. It takes into account the initial rooftop potential in kWp and the average size that is needed per kWp.	
(37)	IN PV Module Price = INITIAL(60.8) This is the initial value for the PV Module price at the beginning of the simulation.	Price index
(38)	IN rooftop potential = INITIAL(1.29818e+08) This is the initial value for rooftop space that can be used to install PV systems. Data based on Quaschning (2000, p. 164).	kWp
(39)	Installation Rate = Demand in PV/Time to Install This is the inflow adjusting for the newly installed PV capacity per year. It is assumed that demand can be satisfied, i.e. that there is no excess demand and capacity constraints on the supply side are excluded.	kWp/ year
(40)	Installed PV Capacity = INTEG(Installation Rate-Degradation Rate, IN Installed PV capacity) The stock accumulates the cumulated installed PV capacity in kWp. It refers to the peak output of installed PV systems.	kWp
(41)	Installed PV Capacity DATA = WITH LOOKUP (Time) Look up ([(2002,392)-(2018,5e+07)],(2002,296000), (2003,435000),(2004,1.105e+06),(2005,2.056e+06),(2006,2.899e+06), (2007,4.17e+06),(2008,6.12e+06),(2009,1.0566e+07), (2010,1.8006e+07),(2011,2.5916e+07),(2012,3.4077e+07), (2013,3.671e+07),(2014,3.79e+07),(2015,3.9224e+07), (2016,4.0679e+07),(2017,4.2339e+07),(2018,4.5277e+07)) This is the reference data for the Installed PV capacity from 2002 to 2018. Data source: BMWi (2019b).	kWp
(42)	Interest Rate = Interest Rate DATA (Time) This function returns the value of the real interest rate from 2012 to 2018.	Dmnl
(43)	Interest Rate DATA [(2002,0)-(2018,0.08)],(2002,0.0778),(2003,0.069), (2004,0.0718),(2005,0.0621),(2006,0.059),(2007,0.0641), (2008,0.0632),(2009,0.0606),(2010,0.0657),(2011,0.0657), (2012,0.062),(2013,0.0616),(2014,0.0594), (2015,0.0597),(2016,0.0567),(2017,0.0537),(2018,0.0581) This is the exogenous input for the interest rate, i.e. financing costs of bank loans from 2002 to 2018. Data source: Deutsche Bundesbank (2019) and taken for the month of December each year.	Dmnl
(44)	Learning = Installation Rate This inflow represents the experience gained by producing PV systems.	kWp/ year
(45)	Learning Curve Factor Modules = LOG(0.8,2) This represents the constant that defines the magnitude of the learning effect, i.e. The higher the learning curve factor, the higher the relative learning effect given a certain increase in cumulative experience. It is assumed that prices fall by 20% once the output has doubled. (Freisberg, 2005)	Dmnl
(46)	Marketing Effectiveness = IF THEN ELSE(SWITCH Scenario 2 = 1 :AND: Time>=2006, Marketing Effectiveness Scenario 2, Marketing Effectiveness Base Run and Scenario 1) This variable returns the effectiveness of social exposure gained by marketing and awareness programmes about PV. SWITCH Scenario 2 = 0 for Base Run and Scenario 1; = 1 for Scenario 2.	1/year
(47)	Marketing Effectiveness Base Run and Scenario 1 = 0.01 This parameter represents the effectiveness of social exposure gained by marketing and awareness programmes about PV in scenario 1 and the Base Run.	1/year
(48)	Marketing Effectiveness Scenario 2 = 0.025 This parameter represents the effectiveness of social exposure gained by marketing and awareness programmes about PV in scenario 2.	1/year
(49)	Maximum decay rate = 0.95 This is the maximum forgetting rate.	1/year
(50)	Potential Demand = IF THEN ELSE(Potential space for PV Installations>0, ((Potential space for PV Installations/Average PV size)) , 0) This variable delivers the PV potential demand in kWp calculated by the total potential space as well as the average size that is needed by 1 kWp of a PV system. Potential demand can only exist if there is enough space to install PV systems.	kWp
(51)	Potential Demand Familiar with PV = Familiarity with PV*Potential Demand This variable represents the fraction of the potential demand that is also familiar with PV and considers it seriously in their purchase decision.	kWp
(52)	Potential space for PV Installations = INTEG (Change in Potential PV Space, IN Potential space for installation) This stock captures the total rooftop space in km² that could be used to install PV capacity. It is adjusted by the installation and degradation rates. However, the overall available rooftop potential is assumed to be constant.	km²
(53)	Profitability of Investments in PV = (Established FIT-PV Investment Costs)/PV Investment Costs This variable represents the profitability or returns of the investments in PV capacity. It includes the PV financing costs (interest rates of bank loans and the price index of PV systems) and the net income per produced kilowatt (FIT) fed into the electricity grid.	Dmnl
(54)	PV BoS Costs = PV BoS Costs DATA(Time) This variable captures the Balance of System Costs associated with installing PV systems. These costs include the power inverter, installation, planning costs and the grid connection. It is assumed that any cost reductions are fully passed into price.	Price index

(55)	PV BoS Costs DATA [(2002,0)-(2018,40)],(2002,34),(2003,27.2),(2004,24.4),(2005,22),(2006,20.95),(2007,17.05),(2008,16.32),(2009,16.7),(2010,14.9), (2011,13.91),(2012,10.58),(2013,10.95),(2014,10.23),(2015,10.13),(2016,10.32),(2017,9.3),(2018,8.9) This is the lookup for the BoS Costs DATA. Data for 2006-2018 has been retrieved from Wirth (2019a), the data for 2002-2006 has been calculated based on the average cost decreases.	Price index
(56)	PV Capacity Gap = PV Capacity Government Cap-Installed PV Capacity This is the difference between the government-set PV cap and the actual installed PV capacity.	kWp
(57)	PV Capacity Government Cap = IF THEN ELSE(SWITCH Scenario 1 and 2 = 0, 5.2e+07, PV Capacity Government Cap Scenario 1 and 2) The installed PV capacity cap is set by the German government. Once the cap is reached, FIT rates will be abolished completely. Originally, the cap was set to 52000000 kWp. (BSW-Solar, 2018)	kWp
(58)	PV Capacity Government Cap Scenario 1 and 2 = 1.2e+08 This is the assumption that the government PV capacity gap was implemented in 2012 but was set higher.	kWp
(59)	PV Investment Costs = PV System Price*(1+Interest Rate) This variable represents the PV investment costs which are made up of the PV system prices and financing costs of bank loans, i.e. the interest rate.	Price Index
(60)	PV Module Price = IN PV Module Price*Effect of Learning on Module Price This variable represents the price of a PV module after the learning effect has been taken into account. It is assumed that any cost reductions are fully passed into price.	Price index
(61)	PV System Price = PV Module Price+PV BoS Costs This variable represents the price of a PV system which is made up of the PV module costs and the BoS Costs.	Price index
(62)	PV System Prices DATA = WITH LOOKUP(Time) Lookup ([(2002,0)-(2018,100)],(2002,94.82),(2003,91.33), (2004,86.58),(2005,81.8),(2006,72.245),(2007,65.56),(2008,62.763),(2009,46.381),(2010,40.264),(2011,30.244), (2012,22.038),(2013,21.469),(2014,20.055),(2015,19.487),(2016,19.471),(2017,17.228),(2018,17.059)) This lookup returns the reference data for the PV System Prices from 2002 to 2018. Data for 2002-2005 from Kosten der Photovoltaik (2016) and from 2006-2018 from Wirth (2019a).	Price index
(63)	Reference Rate of Social Exposure = 0.075 This is the reference rate of social exposure where familiarity decreases at half of the normal rate.	1/year
(64)	Relative Attractiveness of PV = Expected Profitability+Rush to Install PV This variable captures the effect of different attractivity drivers, i.e. rush to install and profitability on the overall attractivity of PV. It is the sum of the Rush to Install and the Expected Profitability of PV. It is hence not constrained between 0 and 1 but varies according to the size of the investment impulse and the profitability of PV.	Dmnl
(65)	Rush to Install PV = IF THEN ELSE(FIT Variation>0, FIT Variation/Established FIT, 0) This variable captures the effect of a rush or hurry in PV under current conditions. Its amplitude depends on the FIT percentage reduction. It is assumed that there is only a purchasing impulse when the FIT is expected to decrease. This means, potential investors do not hold back demand in anticipation of higher FIT renumeration.	Dmnl
(66)	Share of PV Capacity in Total Power Generation Capacity = ZIDZ(Installed PV Capacity, Total Installed Net Power Generation Capacity) This variable represents the ratio of the total PV installed capacity to the total power generation capacity in Germany.	Dmnl
(67)	Slope of decay rate = 1/(2*Reference Rate of Social Exposure) This represents the slope of the decay rate at a given point. It normalises the elasticity of the familiarity decay to exposure at 1.	year
(68)	Social Exposure from PV nonusers = Effectiveness of Contacts with Nonusers*(1-Share of PV Capacity in Total Power Generation Capacity)*Familiarity with PV This variable captures the effect of WoM between PV non-users. This includes, for instance, when a wind energy user and a gas user talk about PV. The familiarity of these non-users with PV depends on the overall familiarity.	Dmnl/ year
(69)	Social Exposure from PV Users = Share of PV Capacity in Total Power Generation Capacity*Effectiveness of Contacts with PV Users*1 This captures the effect of WoM about PV arising from PV users. It is the social exposure acquired by, for instance, seeing PV on rooftops or talking to their owners. It is assumed that everyone of the PV users is fully familiar with PV. Hence, the term is multiplied by "1".	Dmnl/ year
(70)	SWITCH Scenario 1 = 0 This is a switch used for scenario analysis. If switch = 0 = base run, scenario 2; switch = 1 = scenario 1	Dmnl
(71)	SWITCH Scenario 1 and 2 = 0 This is a switch for scenarios 1 and 2. 0 = Base Run, 1 = Scenario 1 and Scenario 2	Dmnl
(72)	SWITCH Scenario 2 = 0 This is a switch used for scenario analysis. If switch = 0 = base run, scenario 1; switch = 1 = scenario 2	Dmnl
(73)	Time delay in demand creation = 1	year

	This is the time people need to create actual demand in PV. This means that people do not react immediately to changes in attractivity factors, rather it takes time to decide to buy a PV system.		
(74)	Time to form Expectations = 0.3 This is the time needed by all investors to realise the profitability of photovoltaic. This includes gathering information and adjusting expectations.	year
(75)	Time to Install = 0.2 This is the time it takes from purchasing the PV system until it is fully functioning and running. This includes planning and approval procedures as well as the actual installation. (Al Yaquob & Yamaguchi, 2015)	year
(76)	Total Installed Net Power Generation Capacity = Total Installed Net Power Generation Capacity DATA(Time) This function returns the value of the total installed net power generation from 2002 to 2018. It represents the total installed electricity generation capacity including all forms of electricity (brown coal, solar, gas, wind,...)	kWp
(77)	Total Installed Net Power Generation Capacity DATA [(2002,1e+08)-(2018,3e+08)], (2002,1.1516e+08), (2003,1.1678e+08), (2004,1.2143e+08), (2005,1.2322e+08), (2006,1.2652e+08), (2007,1.3106e+08),(2008,1.3602e+08), (2009,1.4428e+08),(2010,1.5631e+08),(2011,1.5437e+08), (2012,1.6518e+08),(2013,1.741e+08),(2014,1.8162e+08), (2015,1.8987e+08),(2016,1.9677e+08), (2017,2.0251e+08),(2018,2.06e+08) This is the lookup of the total installed net power generation capacity for 2002-2018. Data source: Fraunhofer ISE (2019)	kWp
(78)	Total Social Exposure = Marketing Effectiveness+Social Exposure from PV nonusers+Social Exposure from PV Users This variable captures the total social exposure from the three different sources.	1/year

Table A4. Model equations

Appendix F. Substructure: Formation of Potential PV Space

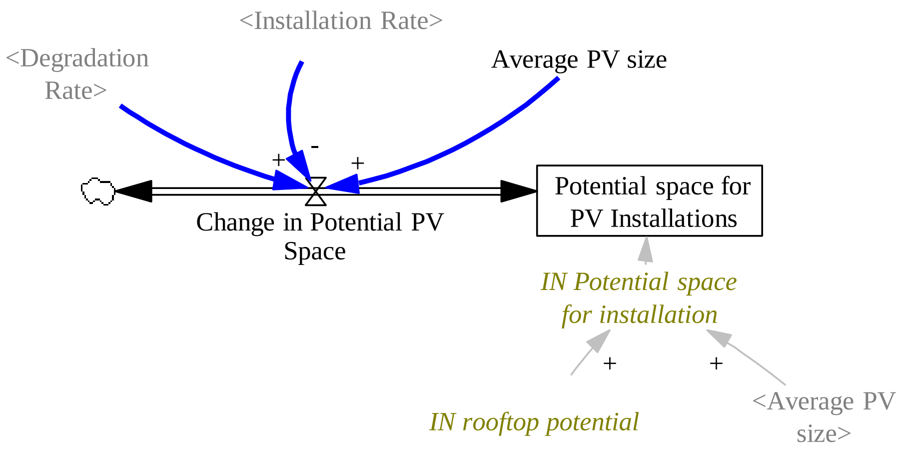

Figure A4. Substructure: Formation of potential PV space

Appendix G. Weekly Average Power Balance of an Electricity Supply in Germany with 200 GWp Photovoltaic and each 50 GWp Onshore and Offshore Wind Power

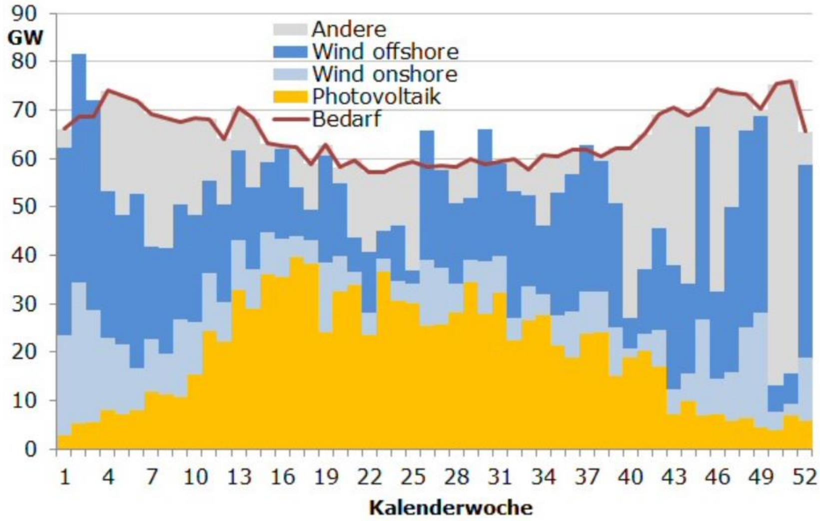

Figure A6. Hypothetical power balance with wind and solar energy (Quaschning, 2012)

Supporting Material

The Vensim file of the SD model is attached along with all experimental runs that we conducted and outlined in this study. The historical data for confidence building purposes is formulated as lookups in the SD model of the German PV market.

Attachments:

- Vensim file of the simulation model of the German PV market with
    - Experimental runs:
        - Base run
        - Scenario 1: Harmonized FIT degression rates
        - Scenario 2: PV awareness programmes
    - Historical Data, i.e. reference data formulated as Lookups