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An economic analysis of agrophotovoltaics: Opportunities, risks and strategies towards a more efficient land use

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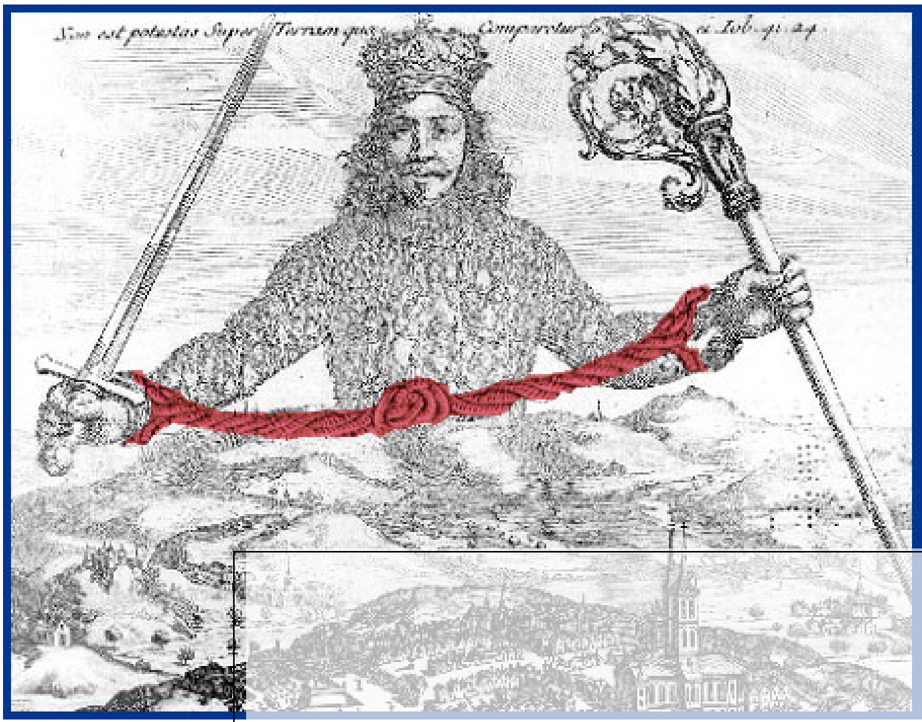

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*An Economic Analysis of Agrophotovoltaics: Opportunities, Risks and Strategies towards a More Efficient Land Use**

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Acronyms and Abbreviations

Bavarian LfL	Bavarian State Research Center for Agriculture
Fraunhofer ISE	Fraunhofer Institute for Solar Energy Systems
a	Year
APV	Agrophotovoltaic
APV-RESOLA	AgroPhotoVoltaic RESOurce-efficient LAnd-use
BMEL	Federal Ministry of Food and Agriculture
BMWi	Federal Ministry for Economic Affairs and Energy
BOS	Balance of System
CAPEX	Capital Expenditures
CAPM	Capital Asset Pricing Model
CM	Contribution Margin
CO_2	Carbon Dioxide
COP	Cost of Production
EEG	German Renewable Energy Act
FAOSTAT	Food and Agriculture Organization of the United Nations, Statistic Division
FIT	Feed-In Tariff
FOC	First Order Condition
GHI	Global Horizontal Irradiance
GMPV	Ground-Mounted Photovoltaic
ha	Hectare
IEA	International Energy Agency
IRR	Internal Rate of Return
KTBL	Association for Technology and Structures in Agriculture
kWh	Kilowatt hour

LCOE	Levelized Cost of Electricity
LER	Land Equivalent Ratio
m^2	Square meter
NP	Net Profit
NPV	Net Present Value
OPEX	Operational Expenditures
PV	Photovoltaic
RE	Renewable Energies
STC	Standard Test Conditions
StMELF	Bavarian State Ministry for Nutrition, Agriculture and Forestry
W_p	Watt-peak
WACC	Weighted Average Cost of Capital

Nomenclature

C	Capacity of installed $\mathrm{kW_p}$ per ha [$\mathrm{kW_p}$/ha]
C_d	Cost of dept [%]
C_e	Cost of equity [%]
$D(\cdot)$	Difference between hypothetical and real mono production in the presence of hybrid production
$E(\cdot)$	Electricity production function
$F(\cdot)$	Food production function
N	Durability [a]
P_d	Share of dept [%]
P_e	Share of equity [%]
S	Annual insolation [kWh/ha]
W	Wealth
X	Total land area
α	Productivity of hybrid food production compared to mono technology [%]
β	Beta-factor
β	Productivity of hybrid food production compared to mono technology [%]
$\delta(\cdot)$	Difference between status quo electricity production and total electricity production in the presence of hybrid production
$\hat{x}_e$	Status quo land allocation for electricity production
$\hat{x}_f$	Land allocated for food production in the status quo
μ	System effectiveness [%]
d	Annual decline of efficiency [%]
$d(\cdot)$	Difference between status quo food production and mono food production in the presence of hybrid production
dt	Quintile $\hat{=}$ decitonne

r_f Market return risk-free [%]

r_m Market return historic [%]

s Share of land allocated for hybrid production that in the status quo was allocated to food production [%]

x_e Land allocated for electricity production

x_f Land allocated for food production

x_h Land allocated for hybrid production

1 Introduction

The way we produce food and generate energy substantially matters for major challenges of this century.[1] Agricultural practices affect biodiversity, human health and quality of water; fossil-fuel power stations drive Carbon Dioxide (CO_2) emissions exacerbating global warming; and efficiency of both sectors co-determines how many people do have access to food and energy supply.[2]

Seen in this light, it seems plausible that both sectors are – at least in most industrial countries – widely regulated (see e.g. Sumner, Alston, and Glauber, 2010; Pearce, 2002). Indeed, externalities, public good characteristics, spillovers, and issues of just distribution are frequently cited to justify regulations. In such an environment and given rapid changes and developments of today's energy and food branches, it is an indispensable task of efficient governance to constantly monitor and assess technological innovations, either with respect to their eligibility to get supported or with respect to needs of restriction or prohibition. Recent examples of such a process entered the public debate under the headings of genetically modified crops, promotion of Renewable Energies (RE) or hydraulic fracturing.

In Germany where this thesis focuses on, the recent legal environment with respect to promotion of RE particularly urged for a thorough assessment of available technologies. Year by year or even monthly the scope and amount of governmentally guaranteed Feed-In Tariffs (FIT) changed, always chasing after latest technical and economical developments. Most prominent example is PV, electricity generated by solar power. Beneath the dramatic decline of overall PV-FITs, in 2010 systems of Ground-Mounted Photovoltaic (GMPV) were excluded from receiving FITs. The debate accompanying this decision was a highly controversial one. While on the one hand GMPV-systems are the most cost-efficient way to generate PV-electricity, counterarguments frequently entering the discussion targeted issues of land-use and competition between farmers and investors with respect to available land.

One possibility to overcome those conflicting goals is Agrophotovoltaic (APV), a combined land-use of food and electricity production. This thesis analyses APV in terms of economic efficiency. It develops a theoretic background to assess welfare implications and provides a detailed analysis of earnings and expenditures to assess economic performance of an APV-system. Main findings of this thesis are (1) a welfare criterion defining the productivity of an APV-system required to enhance social welfare; and (2) that APV-plants operate profitable if FITs range between those of large GMPV-plants

[1] Current major challenges of mankind as defined e.g. by the Milenium Project (Glenn, Gordon, and Florescu, 2014).

[2] Beneath efficiency, distributional aspects unquestionably operate as a further crucial determinant.

and small scale rooftop systems.

After presenting the technology of APV in section2, section 3 introduces a simple model of APV that illustrates land use competition and the opportunities APV might offer in this context. Section 4 analyzes commercial efficiency of APV. Starting from a dynamic analysis of revenues and expenditures, we first scrutinize agricultural farming processes before investigating in sales and cost of GMPV-systems. In a third step we adjust relevant parameters to APV-specific levels. This is done based on estimations, interviews with experts and data from an APV pilot project of the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE). Highlighting higher risks and cost compared to conventional GMPV-plants, we apply the results estimating required FITs as a political strategy to support APV. The last sections discuss results, further implications, and conclude.

2 Agrophotovoltaic – Dual Land Use Producing Food and Energy

APV describes dual usage of land for photovoltaic and agricultural production at the same spot. Alternative terminologies frequently characterizing the same technology are "Agrivoltaic" and "Agrovoltaic" (see e.g. DUPRAZ et al., 2011; DE SCHEPPER et al., 2012).

Originally, the idea was developed by GOETZBERGER and ZASTROW (1982) who showed that, if Photovoltaic (PV) panels are mounted at a sufficiently high level, about two third of the solar radiation reaches the surface below (see Fig. 1). Further the authors illustrate that this radiation distributes almost uniformly over the day such that homogeneous plant growth could be realized.

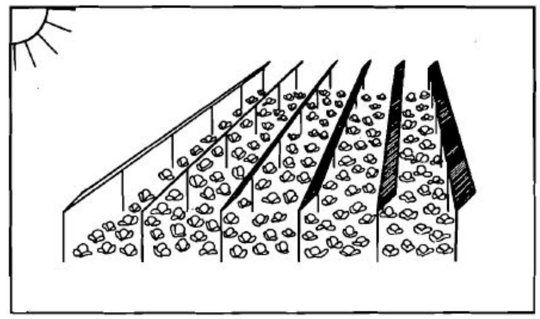

Figure 1: Schematic illustration of an APV-system. Source: GOETZBERGER and ZASTROW (1982)

While in these early days the idea of generating electricity by large PV power plants was a quite visionary one, the widespread existence of nowadays GMPV-systems suggests that an efficient implementation of APV-systems might also become true. In Germany 2014, GMPV accounts for 23% of total installed rated PV-output which is 5.1% of total installed RE or 1.3% of total electricity consumption (STATISTA, 2015).

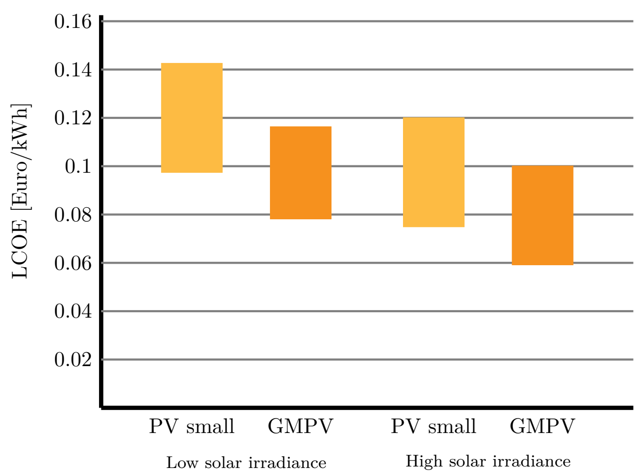

Figure 2: LCOE of small scale PV and GMPV-systems. Source: ISE (2013)

Due to economies of scale, GMPV-systems typically generate electricity at lower cost compared to other kinds of PV-systems (ISE, 2013). Fig. 2 illustrates this relation for regions with low and high solar irradiation, respectively, opposing the Levelized Cost of Electricity (LCOE) of small PV-plants to those of GMPV.[3]

Main benefit of APV-systems is a potential increase in land use efficiency (see e.g. Obergfell, 2012; Dupraz et al., 2011). Given the constant rise in global demand for food and energy[4], land use efficiency is a highly prevalent issue since it might ease the growing pressure on available land currently endangering both biodiversity and existing forms of traditional land use. The relevance of those concerns became apparent through recent debates about land-grabbing activities and biofuel policies (a.k.a. fuel vs. food debates).

Estimating the extent to which APV might contribute to mitigate land use conflicts, the short run perspective essentially differs from the long run. Up to now, the total area globally covered by PV-systems accounts for far less than one per mil of arable land (International Energy Agency (IEA), 2015) indicating that nowadays potential contribution of APV to mitigate issues of land use competition is rather limited. Additionally, risks of a new technology and high cost related to high elevation of AVP-panels are possible drawbacks of APV-systems. In contrast, given the perspective of constantly falling cost and rising efficiency of PV-cells and storage technologies, it seems likely that PV will play a major role within future energy landscapes (Hernández-Moro and Martínez-Duart, 2013). This seems particularly true with respect to PV and energy crops as competing parts of tomorrows energy mix and their respective efficiency per unit of land: Today, average energetic yield of PV-modules is about five times higher than the photosynthetic process of energy crops (15% vs. 3%, see e.g. Dupraz et al., 2011). Moreover, the scope for energy crops is limited due to scarcity of land: Taking Germany as an example, energy crops already account for more than 18% of arable land (Schmidt, Maul, and Haase, 2010) and its unfavorable consequences for biodiversity and quality of soil and ground water have intensively been discussed. Against this background, the long run perspective suggests that PV in combination with storage technologies will win the race against energy crops.

Figure 3: APV-system in Italy. Source: Ahlers (2014)

[3]Low solar irradiation here refers to a Global Horizontal Irradiance (GHI) from 1000 to 1200 kilowatt hours (kWh) per square meter (m^2) and year (a), high solar irradiation to a GHI from 1450 to 2000 $kWh/m^2/a$.

[4]Between 1973 and 2012 the total global food consumption and primary energy supply approximately doubled (Alexandratos, Bruinsma, et al., 2012; IEA, 2014).

3 A Simple Model of Agrophotovoltaic

This section develops a simple welfare model of APV. The first section presents the general set up and underlying assumptions of competitive mono production technologies using land as an input factor. That way we derive a status quo that will serve as point of departure for introducing APV as a hybrid technology. Defining an efficiency criterion we analyze productivity of the hybrid technology required to enhance social welfare.

This section pursues two goals: First and foremost it provides a theoretic structure shedding light on most important implications of the technology; second, it illustrates land use competition and the mitigating role APV might play.

3.1 Basic Set Up

Generally, we follow the assumptions of a neoclassical welfare model considering food (F) and electricity (E) as the only consumption goods of society.[5] Accordingly there are two production technologies, $F(\cdot)$ and $E(\cdot)$, both depending on the same input factor land, where x_f and x_e denote land used for food and electricity production, respectively, with

$$\frac{\partial F(x_f)}{\partial x_f} > 0 \text{ and } \frac{\partial^2 F(x_f)}{\partial x_f^2} < 0 \ .$$

The same applies for electricity production. Since we regard a closed economy and full use of resources, total available land X equals $x_f + x_e$. Further we assume social welfare W to depend on the sum of produced food and electricity. This can be written as

$$W(x_f) = F(x_f) + E(X - x_f) \ .$$

Hence, society chooses an efficient allocation of available land if the optimal level of x_f solves the First Order Condition (FOC)

$$\frac{\partial W(x_f)}{\partial x_f} = \frac{\partial F(x_f)}{\partial x_f} - \frac{\partial E(X - x_f)}{\partial x_f} = 0 \ . \tag{1}$$

In what follows we refer to optimal values of x_f and x_e given by (2) as the status quo levels of the model and denote it with $\hat{x}_f$ and $\hat{x}_e$. Fig. 4 provides a graphical solution of the status quo. As shown in Fig. 4(a), social welfare is maximized if the slope of the production possibility frontier equals the slope of iso-welfare levels.[6] Figures 4(b)

[5]Beneath full information and rational choice, main assumtion here is a benevolent dictator that maximizes social welfare. Further we assume an inner solution with $F, E > 0$.

[6]Iso-welfare lines here refer to areas of equal welfare levels. The analyzed situation implies that society is indifferent between more food or more electricity while, with respect to available land,

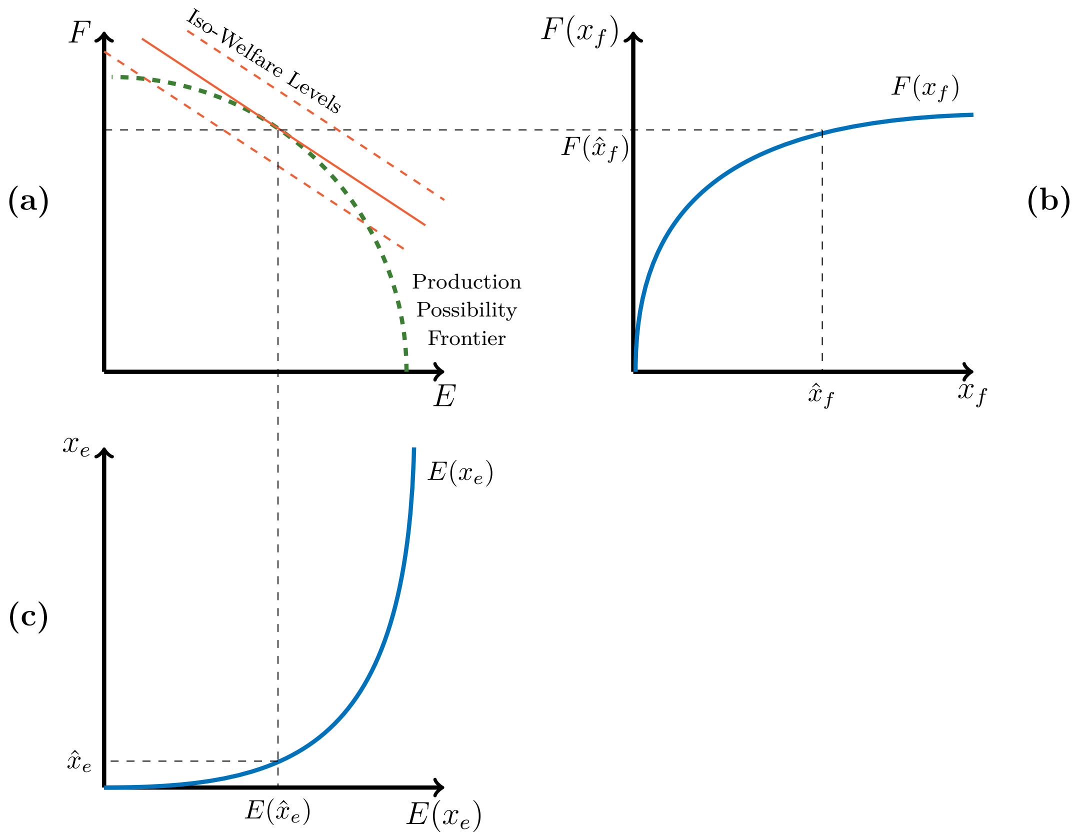

Figure 4: Graphical solution of optimal land allocation. **(a)** Maximized welfare as defined by the slope of iso-welfare levels. **(b)** Optimal food production. **(c)** Optimal energy production.

and (c) depict the optimal contribution of food and electricity production as well as the required levels of x_f and x_e. Note that the graph in Fig. 4(c) follows an inverse shape of the electricity production function in order to adjust axes to those of Fig. 4(a).

production is still feasible.

3.2 Hybrid Technology

Now we introduce a hybrid technology that produces both F and E without rivalry of land. In return, we assume a lower productivity with respect to single good output per unit of land. The reduction of productivity is determined by the parameters α (food) and β (electricity), both ϵ [0,1]. Apart from reduced per unit output, the hybrid technology follows the same production functions as mono technologies.

Now, society can choose to reallocate some amount of land x_h for hybrid technology where $X = x_e + x_f + x_h$. Further we denote s as the share of x_h that in the status quo was allocated for food production. Equally, the share of x_h initially being used for electricity production equals $(1 - s)\hat{x}_f$. Thus, total amount of reallocated land x_h and new levels of x_f and x_e can be written as

$$x_h = sx_h + (1 - s)x_h \ ,$$
$$x_f = \hat{x}_f - sx_h \ , \text{ and}$$
$$x_e = \hat{x}_e - (1 - s)x_h \ .$$

Fig. (5) exemplarily illustrates total food output produced by mono and hybrid technology. Compared to the status quo, there are two effects: On the one hand, mono food production reduces from $F(\hat{x}_f)$ to $F(x_f)$; on the other hand, the hybrid technology contributes to total food production. This amount of food can be expressed by the hypothetical output if land allocated to mono and hybrid production would be used exclusively for mono food production: Since we assume the same production function for both technologies, the difference between this hypothetical and real mono production times α equals the hybrid food production. This is depicted by the red elements in Fig. (5). In the following we refer to the difference between hypothetical and real mono production as the potential contribution of the hybrid technology.

With respect to land reallocation, the segments on the horizontal axis illustrate the shares of x_h which in the status quo were allocated to food and electricity production, respectively. Hence, total food production can be written as

$$F(\hat{x}_f, x_h) = F(\hat{x}_f - sx_h) + \alpha[F(\hat{x}_f) - F(\hat{x}_f - sx_h)] + \alpha[F(\hat{x}_f + (1-s)x_h) - F(\hat{x}_f)] \ , \quad (2)$$

which splits up into three parts: The first term refers to food produced by mono technology; the second one concerns hybrid food production on land originally allocated to mono food technology; and the third one deals with hybrid food production on land

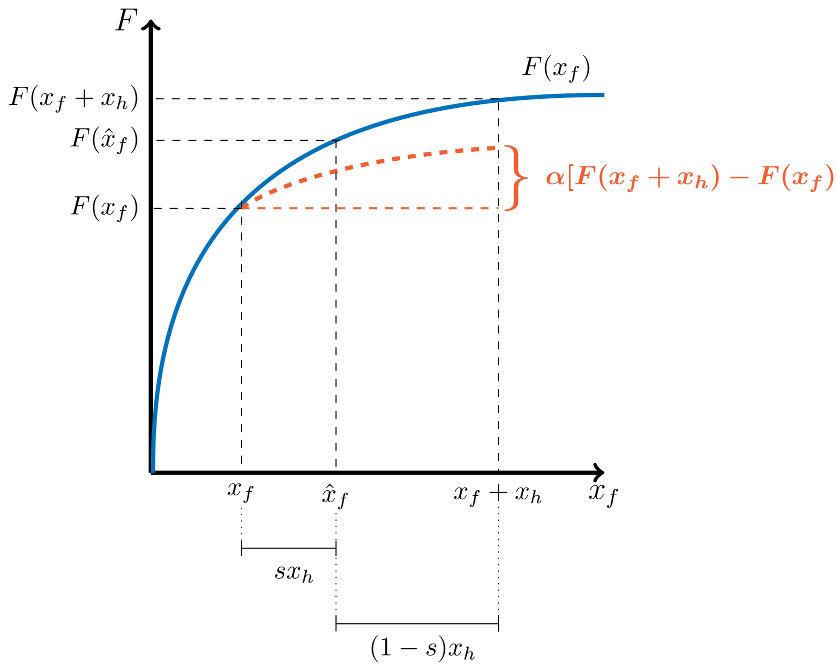

Figure 5: Food produced by mono and hybrid technology

originally allocated to mono electricity production. Simplifying (2) yields

$$F(\hat{x}_f, x_h) = F(\hat{x}_f - sx_h) + \alpha[F(\hat{x}_f + (1-s)x_h) - F(\hat{x}_f - sx_h)]\ . \tag{3}$$

Since the same applies for electricity production, we can describe welfare in the presence of hybrid production as

$$\begin{aligned} W(\hat{x}_f, \hat{x}_e, x_h) &= F(\hat{x}_f, x_h) + E(\hat{x}_e, x_h) \\ &= F(\hat{x}_f - sx_h) + \alpha[F(\hat{x}_f + (1-s)x_h) - F(\hat{x}_f - sx_h)] \\ &+ E(\hat{x}_e - (1-s)x_h) + \beta[E(\hat{x}_e + sx_h) - E(\hat{x}_e - (1-s)x_h)]\ . \end{aligned} \tag{4}$$

3.3 Efficiency Criterion and Sensitivity Analyses

Evaluating efficiency of the hybrid technology, it appears helpful to set up an efficiency criterion. One benchmark that comes naturally is to compare welfare of the status quo with welfare if the hybrid technology is employed.

$$W(\hat{x}_f, \hat{x}_e) = W(\hat{x}_f, \hat{x}_e, x_h) \tag{5}$$

By this means we are now able to analyze the levels of α and β required for the hybrid technology to be efficiency enhancing. Applying (4) and (5) and solving for α yields

$$\alpha = \frac{F(\hat{x}_f) - F(\hat{x}_f - sx_h) + E(\hat{x}_e) - E(\hat{x}_e - (1-s)x_h) - \beta[E(\hat{x}_e + sx_h) - E(\hat{x}_e - (1-s)x_h)]}{F(\hat{x}_f + (1-s)x_h) - F(\hat{x}_f - sx_h)} \tag{6}$$

Scrutinizing this equation, we break it down into three differences. The first difference $F(\hat{x}_f) - F(\hat{x}_f - sx_h)$, here denoted as $d(\cdot)$, addresses food produced solely by mono technology. Subtracting mono food production in the presence of the hybrid technology from the food production in the status quo, $d(s)$ represents losses that occur if less land is allocated to mono food production. Hence,

$$\text{for all } s > 0 \;\rightarrow\; d(s) > 0 \text{ , since } F(\hat{x}_f) > F(\hat{x}_f - sx_h) \text{ .}$$

Further, $d(s)$ is strictly monotonic increasing in s.

The second difference which we denote with $\delta(\cdot)$ represents the change of total electricity production that turns up if the hybrid technology is employed. Thus, $\delta(s, \beta)$ corresponds to electricity production of the status quo less the electricity production in the presence of both mono and hybrid technology, or, formally

$$\delta(s, \beta) = E(\hat{x}_e) - E(\hat{x}_e, x_h) \tag{7}$$

which equals

$$\delta(s, \beta) = E(\hat{x}_e) - \Big\{E\Big(\hat{x}_e - (1-s)x_h\Big) + \beta\Big[E(\hat{x}_e + sx_h) - E\Big(\hat{x}_e - (1-s)x_h\Big)\Big]\Big\} \text{ .} \tag{8}$$

In contrast to $d(s)$, $\delta(s, \beta)$ can be both positive or negative, pointing at the fact that we do not know whether electricity production exceeds the status quo level or not. While a higher β clearly implies a fall of $\delta(s, \beta)$, at first glance the effect of s seems unclear. All other variables remaining constant, a rise in s causes two effects: On the

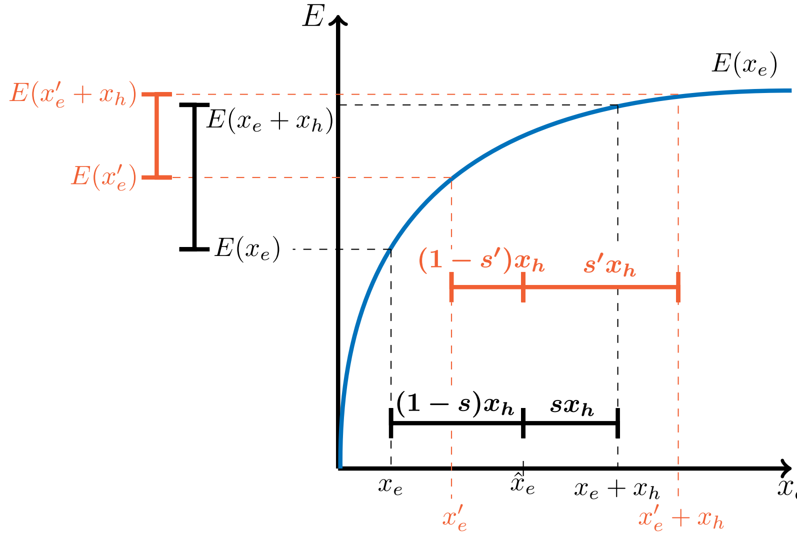

Figure 6: A rise in s leading to lower potential food contribution of the hybrid technology.

one hand it implies that more land is reallocated from mono food to hybrid production which in turn increases the share that remains for mono electricity production. On the other hand an increase in s lowers the share of land allocated to hybrid electricity production thus leading to less losses and a lower $\delta(s, \beta)$; on the other hand an increase in s reduces the potential contribution of hybrid food production. In Equ. (8) this lowers $E(\hat{x}_e, x_h)$ and increases $\delta(s, \beta)$. This effect is visualized by Fig. (6). On the horizontal axis, a rise from s to s' shifts land units allocated for hybrid production to the right. This shift implies a lower potential contribution as shown by the red intercept on the vertical axis. To shed light on the overall impact of s we derive the first derivative of $\delta(s, \beta)$.

$$\begin{aligned}\frac{\partial\delta(s,\beta)}{\partial s} &= -\frac{\partial E\Big(\hat{x}_e-(1-s)x_h\Big)}{\partial s} - \beta\,\frac{\partial E(\hat{x}_e+sx_h)}{\partial s} + \beta\,\frac{\partial E\Big(\hat{x}_e-(1-s)x_h\Big)}{\partial s}\\ &= (\beta-1)\frac{\partial E\Big(\hat{x}_e-(1-s)x_h\Big)}{\partial s} - \beta\frac{\partial E(\hat{x}_e+sx_h)}{\partial s}\end{aligned} \tag{9}$$

Dividing this expression in two parts, it becomes clear that the first one must be negative since

$$\begin{aligned}\beta-1 &< 0 \quad \text{and}\\ \frac{\partial E\Big(\hat{x}_e-(1-s)x_h\Big)}{\partial s} &> 0\ .\end{aligned}$$

In contrast, the second part of (9) is always positive. Hence, the overall value is negative indicating that $\delta(s, \beta)$ must be falling in s.

The third difference of Equ. (6), denoted as $D(\cdot)$ represents potential contribution of the hybrid technology to food output.

$$D(s) = F\Big(\hat{x}_f + (1-s)x_h\Big) - F(\hat{x}_f - sx_h)$$

Alike decreasing marginal productivity that lowered the potential contribution of electricity illustrated in Fig. 6, here a rise in s increases the potential contribution to food production. Summarizing effects of the three differences we can rewrite Equ. (6) as

$$\alpha = \frac{d(\overset{+}{s}) + \delta(\overset{-}{s}, \overset{-}{\beta})}{D(\overset{+}{s})} ,$$

where the superscripts indicate the sign of the marginal effect of s and β, respectively. Evidentially, a high β lowers the required level of α that makes the employment of the hybrid technology welfare enhancing. In contrast, consequences of a change of s partially cancels out.

For further analyses, it seems appropriated to treat s as an exogenous variable since society is free to choose the level of s. For the sake of simplicity we set s equal to 1 assuming that all reallocated land stems from former food production. By that, Equ. (6) reduces to

$$\alpha = 1 - \beta \; \frac{E(\hat{x}_e + x_h) - E(\hat{x}_e)}{F(\hat{x}_f) - F(\hat{x}_f - x_h)} \; . \tag{10}$$

Due to decreasing marginal productivity we know that both the numerator and denominator of the equation above must be greater than zero. This implies that the fraction equals some positive number. To assess the magnitude of the fraction, it appears helpful to assume x_h being closed to zero. Here a x_h of zero can be seen as a situation in the status quo in which society asks for required levels of α and β that makes a reallocation of one marginal land unit from x_f to x_h efficiency enhancing. Analytically, this is done by analyzing the limits of the fraction as x_h approaches 0.

$$\lim_{x_h \to 0} \frac{E(\hat{x}_e + x_h) - E(\hat{x}_e)}{F(\hat{x}_f) - F(\hat{x}_f - x_h)} \; .$$

If we expand the fraction multiplying both the numerator and denominator with x_h^{-1} we can apply Newton's difference quotient (see e.g. Leithold, 1996).

$$\lim_{x_h \to 0} \frac{\frac{E(\hat{x}_e+x_h)-E(\hat{x}_e)}{x_h}}{\frac{F(\hat{x}_f)-F(\hat{x}_f-x_h)}{x_h}} = \frac{\frac{\partial E(\hat{x}_e)}{\partial \hat{x}_e}}{\frac{\partial F(\hat{x}_f)}{\partial \hat{x}_f}} .$$

Thus, the numerator equals the marginal food productivity of the status quo and the denominator equals the marginal electricity productivity of the status quo. From the FOC of the status quo we know that

$$\frac{\partial E(\hat{x}_e)}{\partial \hat{x}_e} = \frac{\partial F(\hat{x}_f)}{\partial \hat{x}_f} .$$

Consequently, the equation takes on a value of 1. For α in Equ. 10 this means that

$$\alpha = 1 - \beta ,$$

or, in other words, the hybrid technology enhances welfare if α and β sum up to more than 1. In Appendix A.1 we show that the opposite case in which $s = 0$ results in the same solution. Hence, as an efficiency rule for the hybrid technology we can write

$$\alpha + \beta > 1 .$$

This ruel is in line with the efficiency benchmark of the Land Equivalent Ratio (LER), a common approach of measuring productivity of combined land use in agroforestry (see e.g. Dupraz et al., 2011). In section 5 we discuss our efficiency rule with respect to real life values.

4 Dynamic Analysis of Revenues and Expenditures

In this section we analyze economic performance of APV with respect to commercial usage. We describe and evaluate factors that determine the level of cost and revenues and estimate the profitability of APV-systems by its expected Net Present Value (NPV) and Internal Rate of Return (IRR). The first subsection illustrates this analysis for common farming practices taking organic potatoes as an example. Providing a rough overview about most relevant work processes and cost items we take this subsection as a point of departure for linking agriculture to an APV-system. The second subsection does the same analysis for standard GMPV-systems. Finally, the third subsection combines both results by adjusting relevant parameters to APV-specific levels. This is done based on estimations, interviews with experts and data from the APV-RESOLA project led by Fraunhofer ISE.

All assumptions concerning solar radiation, factor prices, and agricultural and financial parameters are based on regional data of south Germany in order to adjust the analysis to the APV-RESOLA pilot project in Heggelbach[7]. With respect to the assumed land size we regard an area of 2 hectares (ha) considering both the conditions of the Heggelbach project and real plant sizes of GMPV-systems. With 0.5 ha the dimension of the Heggelbach project is relatively small whereas nowadays GMPV-systems usually require a minimum land size of approximately 20 ha to become competitive (Gimbel, 2015). According to the Heggelbach project, we further assume farming practices of organic agriculture. Considering average durability of PV-systems, we regard a time frame of 25 years.

Since dynamic effects play a major role in assessing the economic performance over time, one crucial parameter is the discount rate. To estimate an appropriate discount rate, we employ the Weighted Average Cost of Capital (WACC) assuming the same financial parameters in the farming and the energy sector. In doing so, we obtain uniform and comparable results in both sectors. However, it should be noted that some parameters considerably differ between the two branches, e.g. the equity ratio which is traditionally much higher in the farming sector (Bavarian State Ministry for Nutrition, Agriculture and Forestry (StMELF), 2014).[8]

If not stated otherwise, all legal regulations like taxes, subsidies and fees follow the current state of law in Germany 2014. As a default case we assume farmers and energy producers being one economic entity. Large values are rounded up to whole € units. All calculations are carried out using Microsoft Excel™.

[7] Region Lake Constance upper Swabia.

[8] See section 5 for a further discussion of these parameters.

4.1 Economics of Agriculture

To perform a dynamic analysis of revenues and expenditures we first illustrate cash flows of the base year regarding earnings, subsidies and a standardized Cost of Production (COP) budget. Than we derive the WACC and employ the latter to discount all future cash flows to their present value. The aim is to estimate an average NPV based on common farming practices in order to draft a baseline scenario which we later adjust to the case of APV.

At first glance it might seem questionable that this inquiry focuses on organic farming practices. Indeed, with a 1% share of global agricultural land, today the certified organic farming sector is still relatively small compared to conventional farming (Willer, Lernoud, and Home, 2013).

However, this share is constantly growing. Further, in Germany and moreover in Baden-Württemberg where this thesis focuses on, the share is considerably above average (6.8% and 8.5%, Federal Statistical Office, 2014; Federal Ministry of Food and Agriculture (BMEL), 2014). Additionally – since mean farm size is significantly smaller in the organic sector than in the conventional one – the share of organic farms in Baden-Württemberg is already above 15%, with this figure set to increase in future. (State Institute for the Environment, Measurements and Conservation in Baden Württemberg (LUBW), 2014) Main reason why we take organic potatoes as an example is, though, to adjust this analysis to the Fraunhofer ISE project in Heggelbach, which follows organic farming practices.

With respect to subsequent years, we assume no crop rotation. Quantities of agricultural yield are given in quintiles (*dt*) which corresponds to 100 kg or one decitonne. All other figures refer to one ha. Further, all assumptions concerning agricultural production follow average values as recommended by the Bavarian State Research Center for Agriculture (Bavarian LfL). A detailed list of cost and revenue items can be found in Annex A2.

4.1.1 Yield, Prices and Revenues

Generally, total revenue of one produced commodity equals total yield times the average price at which the commodity is sold. However, in case of organic potatoes out of total yield only 70% are expected to be suitable for consumption, while 20% can be sold for animal feed and 10% are waste. Additionally, farmers that are working according to ecological guidelines receive subsidies for each ha of cultivated land. Thus, total revenues sum up to

$$\text{Total Revenues} = (\text{Yield} \times 0.7) \times \text{Price}_{cq} + \text{Yield} \times 0.2) \times \text{Price}_{fq} + \text{Subsidies}$$

where Price_{cq} and Price_{fq} refer to potato market prices of consumption quality and feedstuff quality, respectively. Both yield and prices of organic potatoes are relatively volatile compared to other food crops.[9] To account for this fact, we employ average levels of yield and wages as recommended by Bavarian LfL (2015).

To calculate revenues of subsequent years we assume per ha yield of organic potatoes to increase by 25% less than the average rise of productivity of conventional potatoes in Germany (1.36 instead of 1.81 %, see Food and Agriculture Organization of the United Nations, Statistic Division (FAOSTAT), 2015). Based on annual data from 1990 to 2013, we extrapolate future price levels of organic potatoes declining by 0.56% per year compared to overall price levels (FAOSTAT, 2015). In our example, first year's total revenues amount to about €8,984.

4.1.2 Contribution Margin

Within the production process, standard agricultural cost accounting usually distinguishes between two types of costs: General expenses used in producing all commodities; and expenses related to the production of one specific commodity (Association for Technology and Structures in Agriculture (KTBL), 2013). The latter type is needed to calculate the Contribution Margin (CM) of a single production line, i.e. the share that one commodity contributes to a farm's operating result. Even though potatoes are the only commodity in this analysis, we keep this structure calculating first the contribution margin and in a second step the full cost of the production process. By that we ensure that our analysis corresponds to the standard scheme of agricultural cost accounting.

The CM of a production process is defined by total revenues less the sum of variable costs directly related to the production of the respective commodity.

$$\text{CM} = \text{Total Revenues} - \sum \text{Direct Variable Costs}$$

Direct variable cost in the case of organic potatoes splits up in cost for seed potatoes, fertilizers, direct machinery cost, sorting and grading, hail insurance, direct labor cost and direct storage cost. With €1,613 seed potatoes account for more than half of the

[9] Between 2008 and 2013, organic potato prices ranged from €29 to €63 reflecting ample fluctuations in potato yields (see LfL, 2015; Gimbel, 2015).

total direct variable cost. In total, variable cost sum up to €3,162 generating a CM of €5,822.

4.1.3 Indirect Variable Costs, Fixed Costs and Net Profit

Machinery cost, cost for labor and storage, and other costs that are flexible but not covered by the CM are generally considered as indirect variable costs (KTBL, 2013). with €748 the largest share of indirect variable costs in the case of organic potatoes are imputed labor cost. Whether machinery costs are already part of the CM or not usually depends on the share of the machinery that is owned by the farmer. Here we follow the recommendations of the Bavarian LfL assuming no own machines. Hence, all machine cost are covered by indirect variable cost.

Fixed costs in the case of organic potatoes are land cost and imputed costs of capital, land and labor.[10] In the first year, indirect variable cost and fixed cost amount to €1,473. With respect to subsequent years and in contrast to yield and prices we assume all future prices that affect the cost to develop proportionally to overall price level.

Finally, the Net Profit (NP) equals the difference between the CM and the sum of indirect variable cost and fixed cost.

$$\text{NP} = \text{CM} - (\text{Indirect Variable Cost} + \text{Fixed Cost})$$

Hence, for the first year the NP per ha amounts to €4,349.

4.1.4 WACC and NPV

In case an investment comprises capital of both equity and dept, a standard approach to discount future cash flows to their present value is to apply the WACC as a discount factor (Brealey, Myers, and Franklin, 2006). Accordingly, the WACC consists of the share of equity and dept and its respective prices. Additionally, the corporate tax co-determines the WACC since it mirrors the tax advantage of dept capital if expenses for interest payments reduce the tax base. Therefore, the WACC can be written as

$$\text{WACC} = i = P_e C_e + P_d C_d (100 - t),$$

where P_e is the proportion of equity, P_d the proportion of dept, C_e and C_d its respective costs, and t the corporate tax rate. For what follows we employ an equity ratio of 20% which meets the average figures of the last decades in Germany (Adenäuer and

[10] Imputed costs in this context refer to opportunity costs entering the accounting sheet.

Haunschild, 2008). Following recent credit conditions of the German Kreditanstalt für Wiederaufbau (KfW), we assume a C_d of 2.15 % (Gimbel, 2015). The average corporate tax rate in Germany is given by approximately 30% (KPMG, 2015).

	WACC	**Share of equity**	**Share of dept**	**Cost of dept**	**Corporate tax rate**
Parameter	i [%]	P_e [%]	P_d [%]	C_d [%]	t [%]
Value	3.50	20	80	2.15	30

Table 4.1: Financial parameters calculating the WACC

Tab. 4.1 provides an overview of all parameters and its values.

In contrast to C_d and t which are usually given by the financial and legislative environment, C_e can be derived endogenously employing the systematic risk of an investment (Frencha, 2003). This is typically done by the Capital Asset Pricing Model (CAPM) which sets the expected return of an investment equal to a risk free interest rate plus an investment specific risk premium. This relation can be expressed by the formula

$$C_e = r_f + \beta(r_m - r_f)$$

in which r_f is the risk free interest rate, β stands for the risk or, in other words, the volatility of the expected return of the investment, and r_m is the expected return of the market. Generally, the level of r_f can be approximated by governmental bonds – here we employ a r_f of 1.5%. With about 6.5% the r_m is given by historic data of stock markets (Fernádez and Campo, 2011). As a standard value for investment decisions we apply a beta factor of 2 (Bordemann, 2015). All parameters of the CAPM are listed in Tab. 4.2. By that, the cost of equity amounts to 11.5% and the WACC to 3.5%.

	Cost of equity	**Market return risk-free**	**Market return historic**	**Beta-factor**	**Risk premium**
Parameter	C_e [%]	r_f [%]	r_m [%]	β [-]	$r_m - r_f$ [%]
Value	11.5	1.5	6.5	2	5

Table 4.2: Financial parameters calculating the cost of equity

Now the next step is employing the WACC to determine the NPV of the investment. The NPV method aims to assess the economic efficiency on an investment and, hence, whether an investment should be done or not.

A positive NPV indicates a profitable investment while a negative one suggests an unfavorable one. Generally, the NPV equals the present value of all future cash flows. For N time periods the NPV equals

$$NPV = \sum_{n=1}^{N} \frac{NP}{(1+i)^{-n}}.$$

According to this formula and given the presumed cash flows and time frame, the NPV of the investment amounts to €70,557 per ha. Although this figure already contains all fixed cost related to the production process it should be noted that – since we regard an already operating agricultural holding – it might neglect expenses related to initial investment costs when dealing with a startup business. Further one should bear in mind that this figure refers to a field size of 2 ha. Cultivating a smaller (larger) area will, due to economies of scale, result in a lower (higher) NPV.

4.2 Economics of Ground-Mounted Photovoltaic Systems

This subsection illustrates a NPV-analysis for common GMPV-systems. Similar to section 4.1, we first take a look at earnings out of electricity sales before we focus on the cost distinguishing between initial Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) representing costs over the life-time of the system. In a last step, we calculate the NPV and the IRR and derive the average cost per unit of generated kWh known as the LCOE. If not stated otherwise all applied figures stem from data of the BayWa r.e. Solar Projects GmbH, a project partner of the Heggelbach project. As mentioned in section 2, GMPV-systems typically generate electricity at lower cost compared to other kinds of PV-systems due to economies of scale. However, with a size of 2 ha the area we look at is relatively small compared to standard GMPV-plants and, therefore, economies of scale effects are lower than on average.

All figures concerning PV are given in Watt-peak (W_p) which refers to nominal power yields under Standard Test Conditions (STC). For instance, with 2 ha the field size we look at encompasses a total installed capacity of 1,000 kW_p, or 500 kW_p per ha.

4.2.1 Earnings from Electricity Sales

Normally, earnings are the amount of generated electricity times the price at which electricity is sold. Today, however, realized earnings from PV electricity on the open marked are not yet enough to cover the average cost of power generation. Thus, economic performance still depends on governmental support – in our case the German Renewable Energy Act (EEG). In its latest version from 2015, energy producers operating a GMPV-plant obtain FITs only if they successfully participate in a tendering procedure (Federal Ministry for Economic Affairs and Energy (BMWi), 2014). Bidders agreeing to generate energy at the lowest price per kWh receive this FIT for 20 years. Given the expectation that the auction will reveal entrepreneurs with the lowest profit margin it seems reasonable to assume FITs being closed to the real cost. With an average FIT of €0.0917 per kWh among successful bidders the first allocation round lanced in April 2015 seems to confirm this trend (Federal Network Agency, 2015b). Thus, in what follows we assume a successful participation in the tendering procedure with a FIT of €0.0917 per kWh for 20 years. Since we regard a life cycle of 25 years, we assume electricity of the remaining 5 years being sold at a common market price of €0.05 per kWh (Gimbel, 2015).

The amount of generated electricity depends on region-specific parameters – notably annual insolation S – and physical performance of the PV-system. The latter includes durability N, system efficiency μ and an annual decline of efficiency d. Thus, over N years total electrical yield in kWh per installed kW_p follows the formula

$$Electric\ Yield = \sum_{n=1}^{N} S\mu(1-d)^n \ .$$

To obtain figures per ha we multiply electric yield with capacity of installed kW_p per ha (C) which here we assume to be 500 kW_p. By that, over 25 years total earnings sum up to about €1.27 million per ha.

4.2.2 Capital Expenditures

Fixed expenditures that incur once at the beginning of a project are typically labeled as CAPEX. In the case of GMPV, CAPEX incorporate cost for solar panels and the so called Balance of System (BOS) which encompasses all other costs. In earlier days, solar panels contributed by far the larger share. But since learn effects of panel production took place, the relative share of panel cost was constantly decreasing over time (Hernández-Moro and Martínez-Duart, 2013). According to wholesale prices and recommendations of BayWa r.e. Solar Projects GmbH we assume panel cost of €0.52 per W_p – which is 30% less than expenses on BOS.

Components of the BOS include costs for inverters, mounting structures, racking hardware components, combiner boxes and miscellaneous electrical components, fences, the site preparation and system installations, grid connection, as well as system design, management and administration and cost for tendering procedures, legal advice, due diligence. For a detailed overview of all CAPEX see Tab. A.3 in Annex A2.

4.2.3 Operational Expenditures

In contrast to CAPEX, OPEX refer to running costs that incur during the lifetime of a project. For GMPV, OPEX contain costs for land rent, mowing, cleaning, surveillance, monitoring, commercial management, inverter replacement, cost for insurance, provision of repair services and miscellaneous expenses. With more than 30%, cost of commercial management accounts for the largest part of OPEX. With respect to total cost of an GMPV-system, OPEX contribute only about 30% whereas CAPEX account for 70% of total cost. However, over time relative importance of OPEX grew due to above mentioned learn effects of PV-modules. Tab. A.4 in Annex A2 provides a list of all cost items.

4.2.4 NPV, IRR and LCOE

To estimate the NPV of a GMPV-system we apply the same financial parameters as in the case of agriculture. With €2,226 per ha the NPV indicates that an investment in this GMPV-system would be a profitable one.

Closely connected to the NPV method, the IRR measures the required discount factor to realize a NPV of zero.

$$NPV = \sum_{n=1}^{N} \frac{NP}{(1+i)^{-n}} = 0$$

In our example, a NPV of zero would be realized if instead of the calculated WACC of 3.5% we employ a slightly higher discount rate of 3.51% – which is, hence, the IRR of the project. The lower the IRR the less attractive is an investment. If the WACC is greater (lower) than the IRR the NPV is negative (positive). The fact that the IRR is almost equal to the NPV illustrates that the analyzed GMPV-system operates on the verge of profitability.

Looking at the LCOE tells a similar story: With €0.0864 per generated kWh profitability of an investment hinges on higher FIT in order to balance out low prices during the last five years. A slight reduction of the assumed FIT from €0.0917 to €0.0912 would be enough to yield a NPV of zero. Formally, the LCOE are given by the CAPEX and the present value of all OPEX over the present value of total electricity yield.

$$LCOE = \frac{CAPEX + \sum_{n=1}^{N} \frac{OPEX}{(1+r)^n}}{\frac{\sum_{n=1}^{N} S\mu(1-d)^n}{(1+r)^n}}$$

4.3 Economics of APV

Based on previous findings, in this section we assess the change of parameters compared to the baseline scenario if land is simultaneously used for farming and generation of PV-electricity. While there are different approaches of how this dual land use can be implemented, here we refer to the technology as developed by the APV-RESOLA project of Fraunhofer ISE.

In contrast to other approaches that stick to a maximization of electricity yields (see e.g. Goetzberger and Zastrow, 1982; Dupraz et al., 2011) the ISE technology allows to deviate from standard PV-panel configuration considering the agricultural production process as an integral part of the optimization approach. Analyzing this trade-off between agricultural and electricity yields, costs and earnings, the findings of this section [this thesis] aim to contribute to this optimization process. Accordingly, the inclination of and the distance between panel rows differ from those of GMPV-systems obtaining both a higher and a more even distribution of solar radiation on the land surface below. This causes a stronger and steadier plant growth while at the same time electricity yields reduce (Obergfell et al., 2013). Further, with 5 to 6 meters above ground the altitude of installed PV-panels guarantees that all kinds of mechanized field works can be done.

The next subsections present relevant effects and discuss their cause and their impact on parameters and overall efficiency. We assess the magnitude of parameter changes in the prevalent case and consider how these effects affect APV applications in general. A last section summarizes the results and performs some comparative statics.

4.3.1 Parameter Changes and Further Effects in Terms of Agriculture

At first glance, a major concern of a dual land use is the limited availability of solar radiation with its possible drawbacks for plant growth and, finally, agricultural yield. While this is true for light-demanding plants, other plants remain unaffected or even benefit from less sunlight. According to Obergfell et al. (2013) who distinguishe agricultural crops with respect to their eligibility for an APV-system, there exist three categories: Category Minus which shows adverse reactions if exposed to less insolation; category Null which to a large degree remains indifferent; and category Plus to which potatoes belong and which gains in terms of plant growth and yield. As Seidl (2010) shows, if partially covered, Plus-class crops' yield rises up to 12%. While less direct insolation is likely to be one main driver, also micro-climatic effects might help to explain this reaction. Therefore, in the present case we assume yield of potatoes to increase by 4% due to lower solar radiation while later discussing further micro-climatic effects.

The mounting system of PV-panels is another factor expected to reduce the area of arable land and thus agricultural yield. Pillars and other racking hardware components that are connected to the land surface curtail arable area by about 8% leading to a decline of agricultural yield and all other variable cost items that depend on cultivated field size. Indeed, the only cost items not affected by a change of arable land are "other fixed cost" and "land cost". While a reduction of arable land applies to most agricultural crops, fruit-growing farms and crops with larger row distances might rather remain unaffected.

Additionally, the mounting system restricts the availability of working tracks leading to a potential rise in travel distances and labor input. Therefore we assume fuel consumption and labor effort to increase by 2% and 3%, respectively.

Closely related to a rise in travel distances and labor input, restricted working tracks also bear a higher risk of accidents and damages on machines and agricultural equipment. We account for this issue regarding a rise of insurance cost. Since insurance cost are no single cost item but covered by ”other fixed cost” we expect this item to increase moderately by 2.5%.

Regarding PV-panels, a wide range of more or less probable consequences are expected to alter the micro-climate below, with most of these effects being potentially both beneficial and adverse. As the only exception that clearly enhances efficiency, we suppose the balancing effect on local temperature fluctuation to foster agricultural yield by 3%. Other effects like wind deflecting aspects or a higher local humidity underneath PV-panels are ambiguous. On the one hand side crops are less exposed to risks of wind or drought damage; on the other hand less wind and a higher humidity might increase the risk of diseases as well as pest and fungal infestation. Thus, here we assume pro and cons of these effects to perfectly cancel out. Though, in general, notably regarding non-organic farming practices, it seems reasonable to expect a rise in the use of pesticides and fungicides suppressing adverse effects with a slight overall improvement of profitability. Moreover, beneficial micro-climatic effects are likely to be achieved in regions or countries with low or unsteady precipitation, high temperature fluctuation and fewer opportunities of artificial irrigation.

With respect to PV-panels, a further issue is uneven rainwater distribution on the surface below. Similar to the matter of limited solar radiation, the sign and the magnitude of this effect depend on distinct needs of cultivated crops. Since potatoes possess the ability to direct root growth towards regions of higher soil moisture (see Obergfell, 2012, p.31) we expect no significant effect in our analysis. In general, even though more research has to be done in this field, this effect has probably rather negative implications on plant growth.

Furthermore, PV-panels potentially protect crops from hail damage. As we deal only with partial protection we assume a decrease in hail insurance cost of 10% reflecting a cost advantage of €15 per ha.

Beside implications on agricultural production itself, there are aspects of APV that affect overall economic performance of a farm. Among those are lock-in effects that arise if, with respect to future business opportunities, farmers face a lack of flexibility due to an APV investment decision. This is particularly true if – as in the case of APV – the affected time horizon is large and unforeseen contingencies are likely to occur. For instance, the restriction to Plus-class crops might cause opportunity cost if an unexpected rise of Minus-class crops' profitability opens up new business opportunities that cannot be taken since they are not efficient anymore within an APV-system. To account for lock-in effects we impute annual lump-sum costs of €50 per ha and year which, following Schmid (2015), appears reasonable.

Further, electricity yields affect economic performance of a farm since they generate additional earnings and might lower expenses if own electricity is consumed instead of external one. While from a farmer's point of view these issues might be major arguments for an APV-system, here we ignore them since we cover PV-specific aspects in the next section.

Tab. 4.3 aims to provide a complete list of relevant parameters and their expected effect on efficiency of agriculture. The left (right) side of the table presents efficiency enhancing (diminishing) effects each splitting up in four columns: The first describes the cause or the origin of effect; the second names the effect itself; the third determines which parameter are affected in the general case; and the last one quantifies the magnitude and sign at which the respective parameters change in the present case of organic potatoes.

4.3.2 Parameter Changes and Further Effects in Terms of PV

With respect to the PV-system, most changes that affect earnings and cost originate from higher elevation of PV-panels. First and foremost, this requires more and more solid mounting frames and racking hardware components in order to obtain the desired height and to meet increased operational demands due to a higher wind exposure. This leads to a substantial rise in mounting cost. Relying on data from the APV-RESOLA project, we assume both mounting cost and costs for site preparation and system installation to more than double. More exact, expenses increase from €0.330

Effects on Economic Efficiency of Agriculture							
Efficiency Enhancing				Efficiency Decreasing			
Cause	**Effect**	**Affected Parameter**	**Change [%]**	**Cause**	**Effect**	**Affected Parameter**	**Change [%]**
Mounting system	Less arable land	Variable cost	-8%	Mounting system	Less arable land	Yield	-8%
PV-panels	Hail protection	Hail insurance	-10%	Mounting system	Restricted working tracks	Labor	+3%
PV-panels	Less fluctuation in local temperature	Yield	+4%	Mounting system	Higher risk of accidents	Insurance cost	+2%
Lower solar radiation	Higher growth of PLUS-crops	Yield	+5%	Lower solar radiation	Lower growth of MINUS-crops	Yield	±0%
Wind deflection	Lower risk of wind damages	Yield	±0%	Wind deflection	Risk of diseases and pest infestation	Pesticides, Insecticides, yield	±0%
Higher local humidity	Lower risk of droughts	Yield	±0%	higher local humidity	Higher risk of fungal infestation	Fungicides, yield	±0%
Electricity yields	Own consumption of produced electricity	Fixed energy cost	±0%	PV-panels	Uneven rainwater distribution	Yield	±0%
Electricity yields	Earnings from electricity sales	Earnings	±0%	Time horizon of APV-system	Lock-in effects	Opportunity cost	+€50

Table 4.3: Changes of agricultural parameters

to €0.696 per kW_p which equals a rise of 109% compared to conventional GMPV-systems. Also related to higher elevation of PV-panels we expect expenses for system design, management, and administration to rise by 30% due to higher complexity of the system. Jointly, these changes account for a rise in CAPEX of about one third from €1.248 to €1.632 per kW_p. This change implies large consequences on efficiency: Disregarding earnings from agriculture, the NPV of the project drops from €362 to a loss of €154,650.

A further consequence of higher panel elevation is a rise in OPEX if maintenance works and cleaning of PV-panels demand higher efforts compared to ground-mounted systems. Accordingly we expect provision of repair services and cost of cleaning to rise by 5% and 25%, respectively.

Additionally to more complex cleaning operations, also the frequency of the latter is affected by the height of PV-panels. The higher the elevation above ground the lower is the amount of dust and other air particles – hence, less cleaning operations have to be undertaken over time. On average, it is efficiency enhancing to clean PV-panels each 10 years (Gimbel, 2015). With respect to higher elevation of APV-panels we assume this time horizon to extend by 20% or 2 years.

Another side-effect of elevated PV-panels is protection against theft. Taking this matter into account we consider a decline of insurance cost by 25%.

As mentioned above, deviations from standard PV-panel configuration lead to lower electricity yield. This is with respect to two features: Row distances and sun exposure of PV-panels. Greater row distances allowing more direct insulation to reach the agricultural surface below cause a drop in installed capacity per ha of about 32%. With respect to the angle of incidence, the south-east or south-west exposure of PV-panels reduces system effectiveness by 5% (Obergfell, 2012).

Agricultural work affects efficiency through several channels. Among those, three effects can be identified that reduce efficiency: Higher risk of accidents and thus damages of the PV-system leading to a rise of insurance cost (+30%); higher air pollution in terms of dust and other air particles shortening the time periods between cleaning operations (-80% or 8 years); and, since free accessibility for machines implies no fences on the site boundaries, a greater risk of theft drives insurance cost (+10%). On the other hand, though, agricultural work indirectly fosters efficiency. No continuous fence unquestionably implies less fence cost (-90%)[11] and in contrast to common GMPV-systems need of weed controls only remains underneath mounting elements where no crops are cultivated. This reduces cost of mowing by 60%.

Concerning earnings from market sales, prices of electricity are likely to change due

[11] No complete elimination of fence cost since combiner boxes still require some kind of boundary.

to time differentials in feeding electricity into the grid. If prices vary over the day, the deviation of a pure south exposure of PV-panels leads to a shift in electricity generation peaks thus affecting the level of earnings. At which time prices rise or fall depends on the level of demand and supply for electricity. Even though peak demand usually occurs around midday, nowadays the supply also peaks around this time due to high shares of PV-electricity in Germany. Recently, excessive supply of PV even depresses electricity prices shifting the price peak to morning and evening hours. On average, the price differential between morning and evening peaks and midday low is about 15% to 20% (ISE, 2015). Thereby, the future trend of this phenomenon seems clear: The more installed PV-capacity the larger this price differential will be. However, yield peaks of APV-systems do not perfectly coincident with price peaks. Instead, here we presume a time shift of about two hours which results in a price advantage of about 10%.[12]

With respect to land cost, major differences exist dependent on the kind of land use and the status of the tenant. For an average farmer, land rents per ha and year approximately amount to €360 whereas energy investors usually budget €1,500 (Gimbel, 2015). Reasoning behind this differential is a kind of monopoly rent on the part of farmers: Due to local land use plans the choice of qualified areas is limited and strong bargaining positions of land owners – commonly farmers – raise land rents if energy investors are restricted to few available areas. However, since land cost already appeared within the agricultural production budget, here we disregard any additional expenses.[13]

The same applies for earnings out of agricultural production. While generally additional earnings might affect economic performance of GMPV-systems, here we ignore this issue since we already covered agricultural earnings in the previous section. Tab. 4.4 provides a list of relevant parameters and their expected effect on efficiency in terms of PV. As in the case of agriculture, the left (right) side of the table presents effects that improve (reduce) efficiency.

[12] Note that this effect is lower than it might seem since market prices only step in when FITs expire, which in our case is after 20 years.

[13] Additional expenses in case the investor and the farmer are no economic entity we wil discuss in section 5.

Effects on Economic Efficiency of PV							
Efficiency Enhancing				**Efficiency Decreasing**			
Cause	**Effect**	**Affected Parameter**	**Change [%]**	**Cause**	**Effect**	**Affected Parameter**	**Change [%]**
Agricultural work	No need of weed controls	Maintenance cost	–50	Higher elevation of PV-panels	Higher material and labor cost	Mounting cost, Site preparation and system installation	+109
Higher elevation of PV-panels	Decreasing risk of module theft	Insurance cost	–25	Higher elevation of PV-panels	Higher labor and planning cost	System design, management and administrative costs	+30
Higher elevation of PV-panels	Lower pollution of PV-panels	Cleaning cost	+2 years	Higher elevation of PV-panels	More complex cleaning of PV-panels	Cleaning cost	+25
Accessibility for agricultural work	Reduced fence	Fence cost	–90	Higher elevation of PV-panels	More complex maintenance works	Maintenance cost	+5
Farmer as investor	No land cost	Land Rent	–100	Higher row distance of PV-panels	Less absorption of solar radiation	Required area per kWp	+32
No entire south exposure of PV-panels	Peak shift of generated electricity	Market price of electricity	+10	No entire south exposure of PV-panels	Less absorption of solar radiation	System effectiveness	–5
Agricultural yields	Additional earnings from agricultural sales	Earnings	–	Agricultural work	Higher risk of accidents	Insurance cost	+30
				Agricultural work	Higher pollution of PV-panels	Cleaning cost	–8 years
				Free accessibility	Higher risk of theft	Insurance cost	+10

Table 4.4: Expected changes of PV parameters

4.3.3 Results and Comparative Statics

Given the assumptions made with respect to revenues and expenses, an investment in an APV-system seems not to be profitable. This is indicated by a negative NPV of €84.858 per ha. Accordingly, with 1.94% the IRR is 1.57 percentage points below WACC. Main driver for these results is cost related to high elevation of PV-panels.

The NPV of the project splits up in a surplus of €73,812 contributed by agriculture and a loss of €154,650 on the part of PV. Hence, profitability of agriculture is about 5% higher than under mono production. These efficiency gains mainly result from lower variable cost at almost stable yield and earnings. Indeed, there are also gains with respect to PV: Keeping other variables constant, the elimination of land cost reduces OPEX by about 12% alleviating total losses by almost 30%. However, all these benefits are not large enough to balance out the fierce rise in CAPEX. A graphical overview of most relevant cost items is given by Fig. 7. The pie chart on the left shows the structure of agricultural costs within the APV-system whereas the right one depicts this structure for PV-related costs.

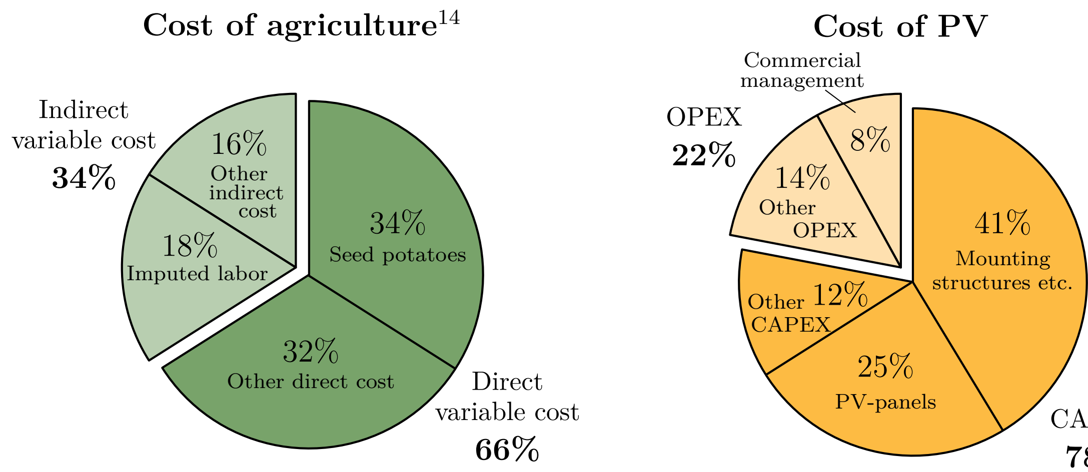

Figure 7: Cost structures of agriculture and PV as parts of APV production

With respect to scope and added economic value, total sales of around €1.1 million per ha split up in €0.17 million from agriculture and €0.93 million from PV. This means, sales from PV are about 5.5 times more worth than those from agriculture. This relation is also prevalent in terms of cost. Fig. 8 illustrates this by the structure of APV cost incorporating agricultural and PV cost of Fig. 7.

Considering potential learn effects related to high elevation of PV-panels, it might be interesting to know the maximum rise of expenses on mounting structures etc. to still attain an equal NPV as expected by the mono PV project. As it turns out, a

[14] Figures refer to first year's budget

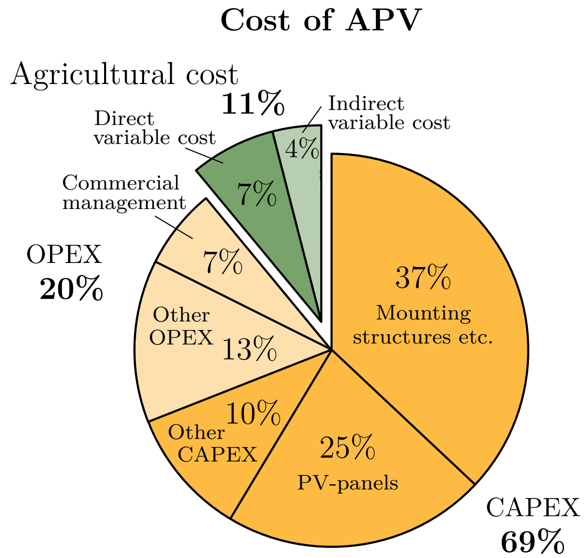

Figure 8: Cost structures of APV production

rise up to 42% could be compensated by efficiency gains and additional earnings from agriculture. Put differently, if cost in terms of elevation of PV-panels rise only by 42% instead by 109%, a PV investor would be indifferent between a conventional GMPV project and an APV project.[15]

As another point of interest, a comparison of LCOE of different PV-systems seems fruitful to asses economic performance of APV-systems. Fig. 9 depicts LCOE of APV together with those of small scale and GMPV-systems. In line with findings above, average costs of APV are higher than those of GMPV. In contrast, compared to LCOE of small scale PV-plants electricity from APV-systems is likely to be cheaper than if produced by rooftop systems.

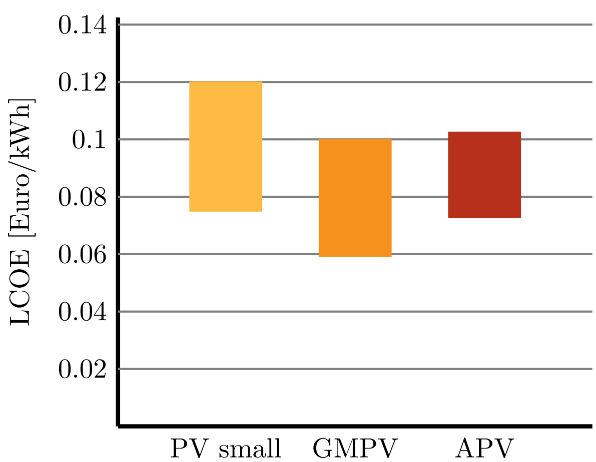

Figure 9: LCOE of small scale PV, GMPV and APV-systems for a GHI between 1,450 and 2,000 kWh/m^2/a. Source: Own representation based on ISE (2013)

If governmentally supported, the relation of different LCOE also mirrors social cost linked to different technologies. Today, PV-systems below 10 kW$_p$ receive a FIT of €0.1234 (Federal Network Agency, 2015a). Following our

[15]Note, though, that this constellation would require further adjustments of parameters since it deviates from our default case in which the farmer is also the investor.

calculations, an APV-system is expected to work cost-effective already at a FIT of €0.1154. Taking into account economies of scale, also FITs below €0.10 are probably enough to ensure efficient operation of larger APV-systems.

5 Discussion

This section discusses main findings of section 3 and 4 and sets them in relation to each other. First we challenge some underlying assumptions of the theoretic model; then we consider possible drawbacks and limitations of the methodology applied for the dynamic analysis of the previous section, reconsidering our standard investor-farmer constellation and briefly touching welfare implications. Finally, we discuss the results with respect to the efficiency criterion developed in section 3 and address future developments and further possible applications of APV.

As a crucial assumption, in section 4 we applied an additive social welfare function to derive optimal allocation of land. Arguably, one could also advocate a multiplicative welfare function since an additive type implies that food and electricity are perfect substitutes for which the marginal rate of substitution is always constant. However, in such a situation society would be indifferent between food and electricity and willed to substitute at the same rate even when it comes to the last unit of food. This seems little realistic. Yet, formally this sort of corner solution is unlikely to occur. As we based the model on production functions with decreasing marginal productivity, the highest productivity exists for the first production units hence simulating a similar optimization behavior as in the case of a multiplicative welfare function. Against this background, the additive and much handier type seems more eligible.

Another assumption that might be questionable is full information. Various regulations of food and energy sectors are motivated by environment issues, notably climate change. Time lags and uncertainties, though, play a major role in explaining why agreements on climate change policies are so hard to obtain. Thus, with incomplete information optimal levels of food and electricity production are much harder to define as the model may suggest.

Likewise, the model completely ignores political decision making and the role of interest groups. In agriculture and energy branches in which public debates, lobbying, and various layers of legislative competences are integral parts of daily life, there is no doubt that a thorough analysis also needs to address these issues.

With respect to the dynamic analysis of earnings and expenditures in section 4, a major methodological drawback is the absence of crop rotation. If potatoes are cultivated on the same field in consecutive years, yield reduces considerably due to plant diseases and pest infestations (Agricultural Chamber of North-Rhine Westphalia, 2012). Hence, the recommended crop-specific rotation period is at least four years. With respect to organic farming methods, a rotation period of seven years is common practice (Schmid, 2015). In the context of this thesis crop rotation is particularly important since average earnings from potatoes are substantially above earnings of other crops leading to an overestimation of the agricultural NPV in section 4. Roughly, we speculate this overestimation to range between 20% and 40%. When performing the calculations with 30% less agricultural earnings, the required FIT to maintain profitability of APV rises from €0.1047 to €0.1133. Still, a detailed analysis including crop rotation seems like a meaningful task for further research.

As a further limitation of APV calculations performed in this thesis, economies of scale are not sufficiently considered. Surely, larger APV-plants perform more efficient. Hence, more specific investigations appear desirable to assess the scope of scale effects and required FITs to support larger plants.

Regarding assumptions about financial parameters, we already mentioned the different equity shares prevalent within farming and energy sectors. This matter is exceptionally important since the share of equity serves as a main driver for the WACC. In turn, the level of WACC has dramatic consequences on the NPV. The average equity capital in the farming sector is about four times higher than in the energy sector.[16] Employing the farming sector's equity ratio rises the WACC from 3.5% to 9.5%. However, we argue that the reasoning behind the difference of equity ratios lies rather in the nature of the investment and not in the origin of the investor. A farmer, usually dealing with high own equity shares with respect to farm investments might face completely different financing opportunities when considering a PV investment. However, it remains to specify whether this holds in reality or not.

Closely related to this issue is the assumption about the investor-farmer constellation. Similar to equity ratio, parameters like land cost, the ownership of land or the legal status are likely to alter if deviating from our default case, and, hence, should be addressed by further investigations.

Estimating the relevance of the APV calculations with respect to the efficiency criterion derived in section 3, the results are little comparable since the calculations do not encompass any welfare effects. However, the fact that productivity of agriculture almost remains constant (referring to an α closed to 1) and productivity of PV only drops by 28% (referring to a β of 0.72) implies that the sum of both parameters is far beyond our efficiency benchmark.[17] A verification of these figures requires a detailed welfare analysis including a quantitative assessment of relevant factors. Partially, this is done by Zangl (2012) who analyzes land use conflicts and APV as a mitigation strategy. Additionally, two other aspects are expected to cause major external effects

[16] Comparing equity shares, with 25% vs. 400% the difference appears to be even larger (StMELF, 2014).

[17] Note that these figures only refer to output per ha and do not reflect involved cost.

and thus need further research. First, since APV would significantly affect the character of landscape, assessments of social acceptance seem indispensable if it comes to policy implications. Second, as a parameter of sustainability, an assessment of the environmental footprint of APV is required in order to illuminate the ecological impact of APV compared to GMPV. Notably, this seems relevant regarding higher resource input related to high elevation of PV-panels. As life cycle assessments of Jungbluth, Tuchschmid, and Wild-Scholten (2008) estimate, mounting structures and hardware components of rooftop systems account for approximately 15% of the system's CO_2 emissions. Comparing the amount of installed materials, it appears probable that CO_2 emissions per installed W_p in the case of of APV-systems are significantly higher compared to GMPV or rooftop systems. Incorporating those welfare effects into the parameter α and β would be task for further research.

6 Conclusion

In this thesis, we analyzed economic performance of APV with respect to land use efficiency, earnings and cost. After presenting the technology as such, we first developed a simple welfare model to provide a theoretic structure of land use competition and technological opportunities. In what followed we examined efficiency of APV with respect to commercial usage performing a dynamic analysis of earnings and expenditures. This was done in three steps: (1) we examined agricultural farming processes, (2) we investigated in earnings and cost of GMPV-systems, and (3) we adjusted relevant parameters to APV-specific levels. By that we emphasized on higher risks represented by rising cost compared to GMPV-systems and estimated FITs required for a political strategy to support APV. Finally we discussed main findings reconsidering underlying assumptions and methodologies as well as possible drawbacks and limitations.

Main finding of the thesis is that APV-plants are expected to operate profitable if FITs lie between those of large scale GMPV-plants and small rooftop systems. For Germany, August 2015, the respective figures are €0.0917 and €0.1234 with APV ranging between €0.10 and €0.12. Concerning theory of land use efficiency, a further finding defines a welfare criterion with respect to productivity of APV as a hybrid technology. Referring to respective mono technologies, the welfare criterion states that the application of the hybrid technology enhances social welfare if it is at least half as productive as the respective mono technology. Applying this result to the analysis of earnings and expenditures suggests that – neglecting any external welfare effects – the employment of APV enhances land use efficiency and thus social welfare. This is in line with findings of Dupraz et al. (2011).

In the context of long term projects like the German Energiewende, the results of this thesis suggest that APV has the potential to be part of future energy landscape. Despite existent drawbacks and open questions discussed further above, APV possibly lowers cost of the energetic transition while at the same time does not consume any additional land. An explicit policy implication, though, requires a public debate about arguments that speak in favor or against APV. This is particularly important in order to clarify which reasons led to an exclusion of GMPV from FITs since two frequently cited arguments point in completely different directions with respect to APV: If aesthetical reasons were responsible APV might even worsen the situation since it affects landscape more than GMPV. However, if competition to common farming is the reason then APV might be an appropriate technology to solve this problem.

A Appendix

A.1 First Part

In this part of the Appendix we provide the derivation of the efficiency rule as done in section 3.1 with the only difference that here $s = 0$ instead of $s = 1$. As in section 3.1 we start from Equ. 6 which is

$$\alpha = \frac{F(\hat{x}_f) - F(\hat{x}_f - sx_h) + E(\hat{x}_e) - E(\hat{x}_e - (1-s)x_h) - \beta[E(\hat{x}_e + sx_h) - E(\hat{x}_e - (1-s)x_h)]}{F(\hat{x}_f + (1-s)x_h) - F(\hat{x}_f - sx_h)} \ .$$

Setting s to 0 yields

$$\alpha = \frac{E(\hat{x}_e) - E(\hat{x}_e - x_h) - \beta[E(\hat{x}_e) - E(\hat{x}_e - x_h)]}{F(\hat{x}_f + x_h) - F(\hat{x}_f)} \ .$$

Now we bracket the term $E(\hat{x}_e) - E(\hat{x}_e - x_h)$ in the numerator of the fraction such that

$$\alpha = (1-\beta) \ \frac{E(\hat{x}_e) - E(\hat{x}_e - x_h)}{F(\hat{x}_f + x_h) - F(\hat{x}_f)} \ . \tag{11}$$

As in section 3.1 we focus on the fraction analyzing the limits as x_h approaches 0.

$$\lim_{x_h \to 0} \frac{E(\hat{x}_e) - E(\hat{x}_e - x_h)}{F(\hat{x}_f + x_h) - F(\hat{x}_f)} \ .$$

Again, first we expand the fraction multiplying both the numerator and denominator with x_h^{-1}. Then we apply Newton's difference quotient.

$$\lim_{x_h \to 0} \frac{\frac{E(\hat{x}_e) - E(\hat{x}_e - x_h)}{x_h}}{\frac{F(\hat{x}_f + x_h) - F(\hat{x}_f)}{x_h}} = \frac{\frac{\partial E(\hat{x}_e)}{\partial \hat{x}_e}}{\frac{\partial F(\hat{x}_f)}{\partial \hat{x}_f}} \ .$$

Thus, the numerator and denominator equal the marginal productivities of the status quo from which we know that they equal each other. Consequently, the equation takes on a value of 1 and all that remains from Equ. (11) is

$$\alpha = \ 1 - \beta$$

which leeds us to the same efficiency rule as in section 3.1.

A.2 Second Part

This section provides detailed figures of cost and revenue items as employed in section 4. Tab. A.1 presents cost and revenue items of agriculture as applied in section 4.1. Additionally, the last collumn shows the corresponding APV figures after the change of parameters as described in section 4.3.1. Changes are highlighted in bold type.

Item	**Unit**	**Baseline scenario**	**APV scenario**
Yield, prices and revenues			
Agricultural yield	dt/ha	246.60	**244.10**
Producer price	€/ha	35.50	35.50
Subsidies for agricultural farming	€/ha	230.00	230.00
Total revenues	**€/ha**	**8,984.30**	**8,896.76**
Contribution margin			
Seed potatoes	€/ha	1,613.20	**1,484.14**
Fertilizer	€/ha	509.89	**464.41**
Direct machinery cost	€/ha	470.30	**432.67**
Sorting and grading	€/ha	224.16	**221.92**
Hail insurance	€/ha	153.20	**136.50**
Direct labor cost	€/ha	100.30	**92.28**
Direct storage cost	€/ha	91.24	**90.33**
Contribution margin	**€/ha**	**5,822.01**	**5.974.50**
Indirect variable cost and fixed cost			
Indirect machinery cost	€/ha	747.89	**710.50**
Storage space	€/ha	164.61	**162.96**
Land cost	€/ha	220.00	220.00
Imputed costs of capital, land and labor	€/ha	243.91	**292.60**
Other fixed cost	€/ha	96.60	**99.02**
Total cost	**€/ha**	**4,635.30**	**4,407.33**
Net profit			
NP	**€/ha**	**4,349.00**	**4,489.43**
Net present value			
Annual growth yield	%	1.36	1.36
Annual growth price	%	-2.36	-2.36
Annual Inflation	%	1.92	1.92
WACC	%	3.50	3.50
NPV (25 periods)	**€/ha**	**70,556.87**	**73,811.84**

Table A.1: Cost and revenue items of agriculture for baseline and APV scenario

The following tables provide figures with respect to PV-related cost and revenue items. Tab. A.2 shows an overview of electrical yield and earnings.

Electricity yield, prices and revenues			
Item	**Unit**	**Baseline scenario**	**APV scenario**
Electricity yield (first year)	kWh/kW_p	1,200	**1,140**
FIT	€/kWh	€0.0917	€0.0917
Market price electricity	€/kWh	€0.05	€0.055
Total	**€/kW_p**	**€2,537**	**€2,437**

Table A.2: Cost and revenue items of agriculture for baseline and APV scenario

Tab. A.3 lists all CAPEX of the baseline and APV scenario. Note that values per ha change even though the actual parameter does not since the installed capacity per ha changes (compare collumns three and five).

CAPEX				
Item	**Baseline scenario**		**APV**	
	in €/W_p	in €/ha	in €/W_p	in €/ha
Solar panels	0.520	260,000	0.520	**197,600**
Inverter	0.075	37,500	0.075	**28,500**
Mounting structures and racking hardware components	0.080	40,000	**0.167**	**63,523**
Combiner box	0.015	7,500	0.015	**5,700**
Miscellaneous electrical components	0.015	7,500	0.015	**5,700**
Site preparation and system installation	0.255	127,500	**0.533**	**202,478**
Fence	0.020	10,000	**0.002**	**760**
System design, management and administrative costs	0.125	62,500	**0.163**	**47,500**
Due diligence	0.025	12,500	0.025	**9,500**
Legal advice	0.013	6,250	0.013	**4,750**
Grid connection	0.100	50,000	0.100	**38,000**
Cost for tendering procedure (fees, risk premia etc.)	0.005	2,500	0.005	**1,900**
Total	**1.248**	**623,750**	**1.632**	**605,910**

Table A.3: CAPEX of the baseline and APV scenario

OPEX				
Item	**Baseline scenario**		**APV**	
	in €/kW$_p$	in €/ha	in €/kW$_p$	in €/ha
Land cost	3.00	1,500	**0.00**	**0**
Mowing	1.80	900	**0.72**	**274**
Surveillance	2.20	1,100	2.20	**836**
Monitoring	3.00	1,500	3.00	**1,140**
Commercial management	7.89	3,945	7.89	**2,998**
Inverter replacement reserve	1.50	750	1.50	**570**
Insurance	0.39	195	0.39	**148**
Insurance (APV-sensitive)	0.97	485	**1.12**	**424**
Provision of repair services	2.00	1,000	**2.10**	**798**
Cleaning	0.65	327	**1.95**	**740**
Miscellaneous expenses	1.46	730	1.46	**555**
Total	**24.86**	**12,432**	**22.32**	**8,483**

Table A.4: OPEX of the baseline and APV scenario

Tab. A.4 provides all OPEX of the baseline and APV scenario.

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