A Brief Overview of Current Methods for Assessing the Operational Stability of Low-Power Grid-Connected Photovoltaic PowerPlants

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Abstract: The article provides a brief overview of modern approaches to assessing the operational stability of low-power grid-connected photovoltaic stations (PV) in conditions of increasing climate stress and grid infrastructure restrictions. Based on an analysis of domestic and international studies, key groups of factors that shape the stability of small PV stations have been systematised: technical, operational, climatic, and integration factors. It is shown that the availability factor is a basic integral indicator of reliability, but its interpretative value is significantly increased when considered in conjunction with MTBF, MTTF, MTTR and CUF metrics. A critical analysis of the impact of equipment failures, climate-induced module degradation, topology features, and the level of digitalisation of monitoring on the operational status of systems is provided. A summary of existing approaches allows us to identify the structural elements of a comprehensive methodology for assessing the operational stability of PV and emphasises the need to develop integrated models capable of taking into account the combined impact of climatic, technical and organisational factors.

1 INTRODUCTION

Between 2010 and 2024, the average annual temperature on the planet increased by more than 0.35 °C, and 2024 was a record warm year: the global temperature anomaly exceeded the +1.5 °C threshold relative to pre-industrial levels for the first time [1]. At the same time, according to data from the IPCC and national climate services, there has been a more than twofold increase in the frequency of extreme weather events such as heat waves, dust storms, abnormal precipitation and storm impacts. These processes have a direct impact on the sustainability of energy systems, reducing the reliability of grid infrastructure and accelerating the degradation of generating equipment [2].

The current research shows the critical impact of climatic factors: high temperatures, sand dust, monsoon rains, and sudden changes in humidity on the performance and degradation of photovoltaic modules. According to global literature, climate-related power losses can reach 5–18% per year, and the failure rate of inverter equipment remains one of the key reasons for the reduction in the availability factor of small PV plants [3]-[6]. In conditions of worn-out network infrastructure and limited automation of monitoring, these processes are exacerbated, leading to increased downtime, uneven generation and higher operating costs.

At the same time, modern research on the sustainability of low-power grid tied PV systems remains fragmented: some studies focus on the analysis of module degradation, others on the fault tolerance of topologies, and still others on climatic effects or digital diagnostics. There is no systematic review combining technical, climatic, integration and operational aspects, which limits the possibility of forming a unified scientific model of operational sustainability.

In this regard, the review uses an expanded approach to assessing the operational stability of low-power grid-connected PV systems. The availability factor is used as a basic integral indicator, but its informative value increases significantly when considered in conjunction with operational and energy indicators such as MTBF, MTTR, CUF, etc., which represent failure frequency, repair duration, actual capacity utilisation, and economic performance, allowing for a comprehensive assessment of the technical, climatic, and organisational aspects of small PV systems. This approach provides a more complete and objective assessment of sustainability in the context of diverse climatic and infrastructural constraints.

2 MATERIALS AND METHODS

The article applies a set of methods aimed at analysing the factors determining the operational stability of low-power PV, such as:

- Systematic bibliometric analysis of domestic and international research on fault tolerance, climate adaptability, and integration reliability of PV.
- Reliability analysis methods used to quantify the impact of key component failures.
- Method of enumerating operational states to compare different PV topologies in terms of their availability.
- Climatic parameterisation, including analysis of actinometric and meteorological data to assess the impact of climatic conditions on module generation and degradation.

The research materials include published results of international projects, monitoring data on small PV, analytical reports, and regulatory documents on the operation of renewable energy sources.

3 RESULTS AND DISCUSSIONS

An analysis of scientific literature indicates several key characteristics of sustainability: technical stability, operational reliability, climate adaptability, integration compatibility, and economic efficiency [7]-[9]. The availability factor, defined as the ratio of actual operating time to calendar operating time, is traditionally used as an integral indicator of operational reliability.

$$AF = \frac{T_{avail}}{T_{total}} \cdot 100\% = \frac{T_{total} - T_{downtime}}{T_{total}} \cdot 100\%, \quad (1)$$

where: T_{total} - total operating time of PV, $T_{downtime}$ - total downtime

Operational stability is also assessed using indicators such as: MTBF – mean time between failures, MTTF – mean time to failure, and MTTR – mean time to repair, which is the average time required to recover equipment. The mean time between failures is defined as:

$$MTBF = \frac{T_{total}}{N_{failures}}, \quad (2)$$

where: T_{total} – total system operating time (hours), $N_{failures}$ – number of failures during this period.

Mean time to failure is a vital indicator, a determining factor in how long a system will operate before its first failure, after which it cannot be replaced:

$$MTTF = \frac{\sum t_i}{n}. \quad (3)$$

To estimate the duration of equipment recovery, the mean time to recovery indicator is used, calculated according to the expression:

$$\text{MTTR} = \frac{T_{recov}}{N_{failures}}, \quad (4)$$

where: T_{recov}– total time spent on fixing all failures (hours), $N_{failures}$ – number of failures during this period.

The combined use of MTBF, MTTF, and MTTR indicators allows for a quantitative description of the main processes of failure and recovery of low-power grid tied PV equipment. However, the operational stability of the system is determined not only by failure statistics, but also by the influence of external climatic conditions, the characteristics of the network infrastructure, and the effectiveness of equipment integration into the network. Therefore, failure time characteristics alone are not sufficient for a comprehensive assessment of stability and must be considered in the context of a broader set of factors that determine the actual availability coefficient and operating modes of the station.

A review of international and domestic literature shows that the operational stability of low-power grid-tied PV systems is influenced by four interrelated groups of factors: technical, operational, climatic, and integration factors. Therefore, in this review, the availability factor is considered as an integral indicator that aggregates the influence of these characteristics and allows for an objective comparison of the stability of different systems under heterogeneous operating conditions.

3.1 Technical Stability and Fault Tolerance

Among the largest international studies on the technical sustainability of renewable energy sources, the study by Milić, et al. [7] occupies a special place, where the FMEA failure analysis method was applied based on long-term monitoring of PV systems in Europe. The object of the study was grid-connected PV systems with a capacity of 5 to 50 MW, operated in different climatic conditions. It was shown that the introduction of new materials reduced the number of critical panel failures by 12% and the overall degradation rate to 0.5% per year (Fig. 1).

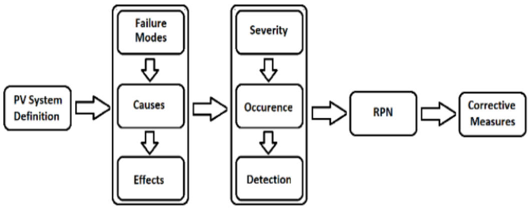

Figure 1: Structure of FMEA/FMECA analysis for PV systems [7].

As a result of modernising connection schemes and introducing a dynamic backup system, equipment downtime was reduced by 8%.

In domestic practice, a comprehensive study of the causes of small PV system failures was conducted by Mirzabaev A.M. [10], Kulmatov Kh.Kh. [11], and Matchanov N.A. [12], and others.

According to the research results by Avezova N.R. et al. [13], it was found that the main reasons for the decrease in technical stability are frequent overloads, degradation of cable lines, and outdated transformers. As a result, the proportion of uninterrupted operation without digital platforms was only 78.8%, while after the integration of intelligent systems, this figure increased to 85.2%.

3.2 Operational Reliability and Intelligent Monitoring

Tao et al. [14] implemented a machine learning-based fault diagnosis and localisation system for A”C in China, which ensured high speed and accuracy of fault detection. As a result, the accuracy of fault diagnosis was 97.8%, which significantly exceeds the performance of traditional methods and contributes to improving the operational availability of equipment (Fig. 2).

Kulmatov Kh.Kh. [11] introduced IoT platforms at small solar power plants in the Fergana Valley and applied automated diagnostic and emergency situation virtualisation systems. As a result, equipment condition monitoring was automated and energy efficiency was increased by 8%.

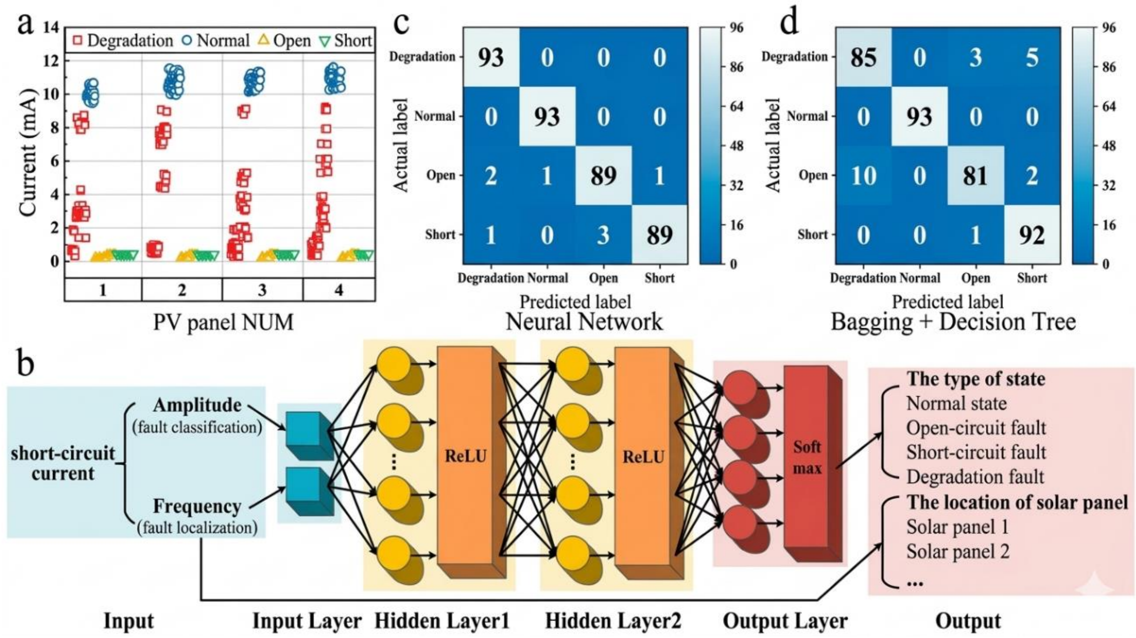

Figure 2: Dataset and results: a) dataset distribution; b) neural network architecture; c) confusion matrix (neural network); d) confusion matrix [14].

In the work of Muminov Sh.A. [15], the operating modes of sustainable solar power plants were studied, and a monitoring system for comprehensive assessment of their sustainable operating modes and a database of climatic and actinometric parameters with high temporal resolution (10 minutes) were developed and implemented (Fig. 3).

It was found that the use of these tools made it possible to increase the accuracy of EE generation forecasts by 8-12% and reduce energy losses due to suboptimal station operation by 3-5%.

3.3 Climate Adaptability and Weather Stability

In his work, Muminov Sh.A. [15] provides a detailed review of scientific works devoted to the influence of various external and internal factors on the effectiveness of PV.

In particular, I. Schweiger et al. [16] investigated the electrical stability of crystalline Si, thin-film (CdTe, Cu(In,Ga)Se, FEM, Ahmed Bouraiou et al. [17] focused on studying the impact of climatic conditions on PV modules installed in the desert region of southern Algeria, including partial shading and sand dust accumulation, which lead to significant power losses and distortion of the I-V characteristics of the modules. M. Malvoni [18] performed a long-term analysis of the performance, losses and efficiency of a 960 kW grid-connected PV system in a Mediterranean climate (Fig. 4).

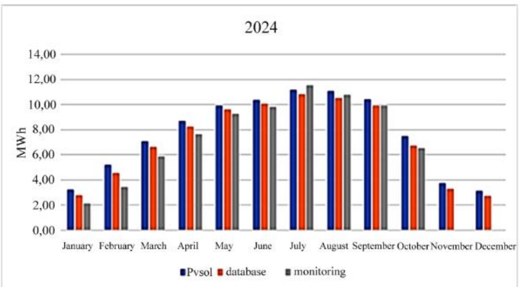

Figure 3: Comparison of the forecast and actual output of a 63.6 kW solar power plant in Fergana in 2024, using a developed solar power plant monitoring system based on PV modules [15].

Meanwhile, Neha Bansal et al. [19] conducted a comprehensive technical, economic, and environmental analysis, studying the causes and consequences of various degradation modes and observed failures in PV systems, as well as evaluating the performance of a 5 MW grid-connected PV power plant operating in the hot and dry climate of Gujarat, India. As a result of a comprehensive analysis based on global research, it was found that the accuracy of PV performance forecasting depends on the quality of data on regional climatic conditions; the use of modelling tools such as SAM and PVSyst minimises errors but requires adjustment based on actual data.

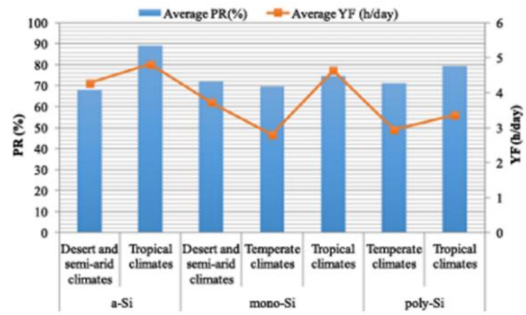

Figure 4: Comparison of performance (average PR and YF values) for different PV technologies in different climatic conditions [18].

3.4 Integration Stability and Standardisation

In their work, Mustafa et al. [20] conducted a quantitative assessment of the reliability of a small 58.3 kW grid-connected PV system. The authors considered three main connection topologies: centralised, string, and multi-string (Fig. 5).

The analysis used the state enumeration method, which allows calculating the probability of system operation in various states based on the failure of key components (PV modules, inverters, connecting elements) and taking into account the influence of variable climatic conditions. The mathematical model is based on the calculation of reliability using the formula:

$$R = \sum_{i=1}^{n} P_i \cdot A_i \qquad (1.2)$$

where P_i – probability of each state occurring, A_i – system availability in this state.

The analysis results showed that the multi-string topology has the highest reliability, with a system availability coefficient of 99.76%. For string and centralised topologies, this figure was 99.42% and 98.94%, respectively.

The key factors determining the reduction in reliability are inverter and cable connection failures.

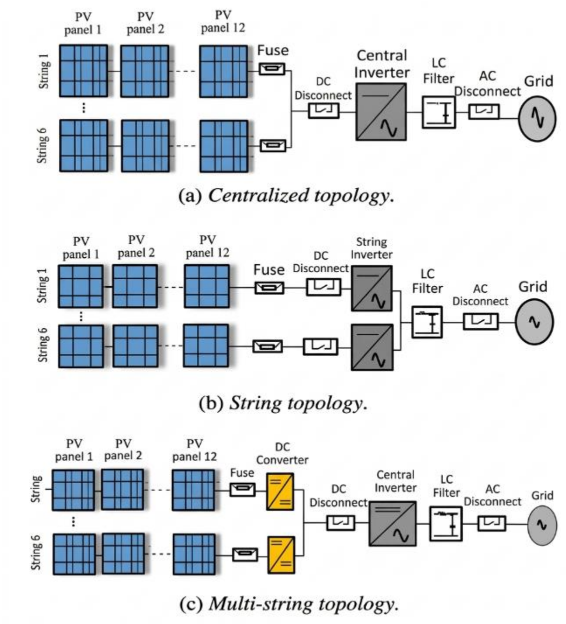

Figure 5: Various FES topologies [20].

Thus, the authors conclude that the use of multi-string schemes in small distributed network PV systems not only provides higher overall system reliability but also minimizes the risk of complete loss of generation in the event of local failures. The presented approach can be used to justify the choice of a circuit and to form a maintenance policy for small PV systems, taking into account the specific operating conditions.

In a study by Matchanov N.A. [12], an analysis was conducted of the average daily, average monthly, and average annual capacity utilisation factors (CUF) of PV systems integrated into low-voltage local electrical networks (Fig. 6).

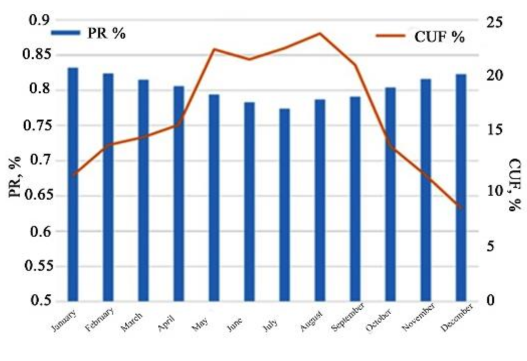

Figure 6: Time dependencies of PR and CUF of the FES integrated into the local network [12].

It has been established that for conditions in Tashkent, average monthly CUF values range from 8.3 to 23.8%.

In addition, the influence of temperature on the output power of PV cells based on mono- and polycrystalline silicon was examined; it was found that the temperature power losses in polycrystalline PV cells are approximately 2% less than in their monocrystalline counterparts.

In their work, Fylladitakis et al. [21] conducted a comprehensive economic analysis of small 6.9 kW grid-connected PV systems in various climatic and economic conditions in Europe (Athens, Berlin, London). The effectiveness was assessed based on the payback period and net present value (NPV) calculations, taking into account the current electricity purchase tariffs and capital costs. The results showed that when the system was implemented in Athens, the payback period was 7.5 years (NPV – €7,850), in Berlin – 10.7 years (NPV – €4,750), and in London – 13.6 years (NPV – €2,190). It was shown that the economic feasibility of projects significantly depends on the level of government subsidies and tariff policy.

The article by Cao et al. [22] provides an overview of modern approaches to optimising the economic efficiency of small grid-connected PV systems, including mathematical models, the formulation of objective functions and constraints, and the optimisation methods used. The data presented demonstrate that with rational organisation and selection of operating parameters, it is possible to achieve a levelised cost of energy (LCOE) of 0.09–0.15 kWh. The importance of organisational aspects, in particular, optimisation of system topology, competent resource management and implementation of modern operating schemes, for increasing project profitability is emphasized.

The work of Thornycroft et al. [23] is devoted to the analysis of the engineering, economic and organisational aspects of the implementation of small network PV systems in the UK, comparing the experience of other European countries. The authors note that in the absence of government subsidies, the payback period for such systems in the UK exceeded 20 years, whereas in countries with developed support programmes (e.g. Germany), it was reduced to 10–12 years. Particular attention is paid to institutional and organisational barriers, including difficulties in connecting to networks, insufficient support programmes and high administrative costs, which significantly hinder the spread of small PV systems.

Thus, a summary of domestic and international studies in recent years, including data from the author's own publications, confirms that the main integral criterion for assessing the reliability of small renewable energy sources remains the availability factor. The effectiveness of all modern solutions is assessed precisely by their impact on this indicator. Contemporary challenges, such as climate adaptation, standardisation, digitalisation, etc., require further scientific and applied research, which determines the relevance and novelty of the dissertation research.

4 CONCLUSIONS

The review confirms that the operational stability of low-power grid-connected photovoltaic power plants is a multi-parameter property formed under the influence of technical, operational, climatic and integration factors. An analysis of international and domestic studies demonstrates that it is the combination of these four groups of factors that determines the behaviour of the system in real operating conditions, and that the availability coefficient is the most representative integral indicator for comparing different configurations and operating conditions of PV stations.

The results obtained show that improving operational reliability is impossible without comprehensive consideration of:

- technical characteristics of equipment, including the failure rate of modules and inverters, degradation parameters, and the quality of the cable infrastructure;
- operational parameters described by AF, MTBF, MTTF, MTTR, and actual operating time indicators;
- climatic effects that determine actual performance losses and generation variability;
- topology and integration scheme that affect fault tolerance and the level of overvoltage in the network.

A comparison of various approaches presented in the literature shows that none of these characteristics alone can adequately describe the operational state of small grid-connected PV. Only their joint consideration forms an objective assessment of the reliability, stability and predictability of the system's operation. This confirms the need to develop comprehensive methodologies based on combining failure statistics, climate trends, structural features of topologies and digital monitoring data.

The review emphasizes that the development of a unified model for assessing the operational stability of small grid-connected PV systems is a critical task for regions with high climatic loads and limited grid modernisation. The conclusions provide a scientifically sound basis for the development of an integrated methodology for assessing stability, which ensures the practical significance of the work and its applicability in the planning, operation and modernisation of small distributed PV systems.

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REFERENCES

[1] Copernicus Climate Change Service, “2024 was the warmest year on record, Copernicus data show,” 2025. [Online]. Available: https://www.ecmwf.int/en/about/media-centre/news/2025/2024-was-warmest-year-record-copernicus-data-show.

[2] IPCC, “IPCC report,” 2025. [Online]. Available: https://www.ipcc.ch/2025.

[3] “Photovoltaic degradation rates - An analytical review,” NREL, [Online]. Available: https://docs.nrel.gov/docs/fy12osti/51664.pdf.

[4] M. Dhimish, R. Vieira, and P. B. Poulsen, “Reliability analysis of residential photovoltaic systems across five climatic zones: Performance, degradation, and fault trends,” Energies, vol. 18, no. 23, p. 6125, 2025, doi: 10.3390/en18236125.

[5] “Degradation of PV modules, inverters, components and systems,” JRC, [Online]. Available: https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/contentype/product_group_documents/1581689975/4_Degradation_Final.pdf.

[6] N. R. Avezova, S. K. Shoguchkarov, and A. R. Kudratov, “Criteria for stability and reliability of grid-connected photovoltaic systems,” Problems of Energy and Informatics, no. 4, pp. 57–72, 2024.

[7] S. Milić, V. Katić, and L. Čičkarić, “Failure modes and effects analysis of urban rooftop PV systems – Case study,” in Proc. Int. Symp. Industrial Electronics (INDEL), 2018, pp. 1–7, doi: 10.1109/INDEL.2018.8637640.

[8] Roy, R. Patil, R. Pimpalkar, and A. Sahu, "A comprehensive review of failure modes and effect analysis of solar photovoltaic system," Materials Today: Proceedings, 2022, doi: 10.1016/j.matpr.2022.11.353.

[9] P. Ganesh et al., "Renewable energy integration in modern power systems: Challenges and opportunities," E3S Web of Conferences, 2024, doi: 10.1051/e3sconf/202459103002.

[10] Mirzabaev, "Matrix methods for stability analysis of electric power systems," Catalogue of Abstracts, vol. 1, no. 1, pp. 1–83, 2023. [Online]. Available: https://inlibrary.uz.

[11] Kh. Kh. Kulmatov, Development and creation of systems for accounting and diagnostics of output parameters of photovoltaic systems, Cand. Sci. dissertation abstract, Fergana, 2024.

[12] N. A. Matchanov, Comprehensive study of photoenergy systems and their integration, Dr. Sci. dissertation abstract, Tashkent, 2021.

[13] N. Avezova, S. Shoguchkarov, and A. Kudratov, "Methodology for calculating the indicator of availability of network PV power plants," Problems of Energy and Sources Saving, no. 1, pp. 106–117, 2025, doi: 10.5281/zenodo.15099748.

[14] Y. Tao, T. Yu, and J. Yang, "Photovoltaic array fault diagnosis and localization method based on modulated photocurrent and machine learning," Sensors, vol. 25, no. 1, p. 136, 2025, doi: 10.3390/s25010136.

[15] Sh. A. Muminov, Modeling of sustainable power supply systems based on PV modules, Cand. Sci. dissertation abstract, Fergana, 2025.

[16] Schweiger et al., "Stability of PV modules in different climates," Progress in Photovoltaics: Research and Applications, vol. 25, no. 12, pp. 968–981, 2017.

[17] Bouraiou et al., "Impact of climatic conditions on PV modules in desert environment," Energy Conversion and Management, vol. 106, pp. 1345–1355, 2015.

[18] M. Malvoni et al., "Long-term performance of 960 kW PV system," Energy Conversion and Management, vol. 145, pp. 169–181, 2017.

[19] N. Bansal, P. Sharma, and A. Gaur, "Visual degradation and performance evaluation of utility-scale PV plant in India," Case Studies in Thermal Engineering, 2021, doi: 10.1016/j.csite.2021.101010.

[20] M. Abu-Elnaga, Y. Hegazy, W. Omran, and A. Mustafa, "Reliability assessment of grid-connected PV systems," in Proc. ICRERA, 2015, pp. 1543–1549, doi: 10.1109/ICRERA.2015.7418666.

[21] E. Fylladitakis and P. Axaopoulos, "Performance evaluation of small PV systems in Europe," 2012.

[22] W. Cao, W. Li, and Y. Du, "Economic operation optimization strategy of PV grid system," Advanced Materials Research, vols. 860–863, pp. 75–80, 2013, doi: 10.4028/www.scientific.net/AMR.860-863.75.

[23] J. Thornycroft, R. Hacker, and D. Munro, "Small grid-connected solar photovoltaic generators in the UK," 1993, pp. 61–66.